THE GLOBAL RESCUE ALARM NET (GRAN)
A SYSTEM ANALYSIS

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NAVAL POSTGRADUATE SCHOOL
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THESIS

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ABSTRACT

The Global Rescue Alarm Net (GRAN) is a proposed Search and Rescue (SAR) system. The purpose of the system is to provide real-time worldwide distress alarm, identification, and position information for the isolated distress case. In the GRAN system a link consists of a handheld Search and Rescue Communicator (SARCOM) unit, a geosynchronous Search and Rescue Satellite (SARSAT) relay, and a processing station, the Search and Rescue Central (SARCEN). This thesis is a system analysis of the proposed GRAN system to generate the broad system requirements. To provide global coverage the numbers and locations of SARSATs and SARCENs are determined. Based on SAR statistical data, SARCOM distribution, multiple access, and probability of interfering transmissions are examined. The SARSAT characteristics such as configuration, antenna gains, and power output are considered in relation to the overall system. From experimental and theoretical data, reference values are chosen which are representative of near-worst case from which the total link can be characterized. From this characterization, system parameters such as SARCEN G/T and SARSAT transmit power can be determined.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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I. INTRODUCTION

The need for a global system for Search and Rescue (SAR) becomes more apparent each year. Many lives are lost annually because the time lag between the distress situation and the receiving of the alert can be a few minutes in the case of an overdue aircraft on a flight plan or several days in the case of an overdue ship at sea. Another factor supporting this need is the lack of common distress frequencies between ships and aircraft. Even though international distress frequencies are assigned, often there is no vehicle within radio range of a distress case that is also monitoring the necessary frequency. Present day communications equipment currently required on U.S. vessels must be operated by personnel. None of this equipment will either activate automatically or continue to operate if the vessel sinks. Even though crash activated radio beacons are in use on aircraft, the problem of being within radio range of the distress case by a monitoring vehicle still exists. For those distress alerts that are received, position information is not always known or received.

Global Rescue Alarm Net (GRAN) is a proposed SAR system which will provide real-time world-wide distress alarm, identification, and position information for the isolated distress case. The need for global coverage will be met by a network of geosynchronous relay satellites that also solves the problem of being within radio range. Position information will be real-time and will not require knowledge of position by the distress case. Transmission format will be automated and will require only a single switch for activation. This, too, could feasibly be crash

activated in the case of aircraft or water activated in the case of ships at sea or aircraft ditched at sea.

Given that the need for a system such as GRAN exists, the intent herein is to do a system analysis of the proposed GRAN system with emphasis on specifying a set of system parameters or range of parameters for which GRAN will be operational.

A. OMEGA

The VLF transmissions of the OMEGA navigation stations provide the signals for position information in the GRAN system. Because OMEGA consists of VLF signals, the system is essentially a long-range navigation system. The spherical waveguide formed between the earth and the ionosphere determines the VLF propagation characteristics. Within short ranges, less than 600 n.mi., of an OMEGA station modal interference prevents a single mode from being dominant. However, between 600 n.mi. and 5000 to 8000 n.mi. the principal mode may be expected to have the lowest attenuation rate and hence dominate, yielding the very long-range navigation signals [1].

World-wide coverage by the OMEGA navigation stations will be achieved by a network of eight stations transmitting with 10 kilowatts radiated power. Since each station will serve approximately three-fourths of the earth's surface, any point will usually be within range of five or six stations providing useful signals [2]. At present there are three OMEGA stations on the air. Table I depicts the current status of OMEGA and its implementation schedule [3]. As indicated, only one of the three OMEGA stations on the air is operating at full rated power of 10 kilowatts. Norway will go off the air in late 1973 to upgrade to 10 kilowatts and Hawaii is presently being upgraded to 10 kilowatts. Trinidad

Station	Status as of June 1973	On Air Date with 10 kW.
North Dakota	on air @ 10 kW.	current
Norway	on air @ reduced power	Jan. 1974
Hawaii	off air for upgrading	Jan. 1974
Japan		Apr. 1974
La Réunion (Indian Ocean)		Jan. 1975
Argentina		Mar. 1975
Trinidad	on air @ reduced power	
Liberia (replaces Trinidad)		Mar. 1975
Australia		1976

Table I. OMEGA Status and Implementation Schedule

will remain on the air at reduced power until its replacement, Liberia, comes on the air at 10 kilowatts.

Each OMEGA station transmits in accordance with the format in Figure 1. As can be seen, the length of each transmission is slightly different and each station has five periods with no transmission presently assigned. Each OMEGA station has a bank of four cesium atomic standards which when intercompared yield frequency accuracies better than one part in 10^{12} [4]. The freqency standards are used in the carrier frequency synthesis and the sequence timing. With transmission sequence timing synchronized so that station A transmits at 0000 GMT each day and every 10 seconds thereafter, station identification is easily determined since the pattern surrounding each station's transmission of a particular frequency is unique. Receiver commutation can be synchronized with the use of WWV or some other time station either manually or in more sophisticated receivers automatically.

Lines of position (LOPs) are derived by comparing phase of one station frequency to phase of a second station same frequency. Since all the OMEGA stations are in phase synchronism, a local reference oscillator is sufficient to determine pair phase difference. This phase difference yields a family of hyperbolic LOPs which are one-half wavelength apart on the baseline between stations. Each family of LOPs represent lanes for which position within a given lane commensurate with measurement accuracy is determined. Since the baseline between stations is on the order of 4000 n.mi. or more, divergence between the hyperbolic LOPs is limited to less than 15 percent as one moves from the baseline. Additionally, because of the long baselines and good station placement, the crossing angles between LOPs will be no less than 60 degrees [5].

START — 10 SECONDS — START → ETC.

TRANSMISSION INTERVAL	0.9	1.0	1.1	1.2	1.1	0.9	1.2	1.0	0.9
STATION A	10.2	13.6	11.33						10.2
B		10.2	13.6	11.33					
C			10.2	13.6	11.33				
D				10.2	13.6	11.33			
E					10.2	13.6	11.33		
F						10.2	13.6	11.33	
G							10.2	13.6	11.33
H								10.2	13.6

0.2 SEC.

Figure 1 OMEGA Signal Format

The OMEGA lane substructure is depicted in Figure 2 and Table II shows how the difference frequencies are derived and the resultant lane widths are given. The primary frequencies of 10.2, 11.333, and 13.6 kilo hertz are presently transmitted with a fourth frequency 10.88 kilo hertz under evaluation [3].

Skywave corrections must be applied to the phase data from each OMEGA station. This correction compensates for the apparent phase shift caused by annual and diurnal changes in the skywave path. These skywave corrections are published in tabular form by the U.S. Naval Oceanographic Office for the stations in operation. Tables for all frequencies and all eight stations will be required for the fully operational OMEGA system.

Difference Frequency	How Derived	$\frac{1}{2}$ Wavelength
10.2 kHz.	fundamental	8 n.mi.
3.4 kHz.	13.6 - 10.2	24 n.mi.
1.133 kHz.	11.333 - 10.2	72 n.mi.
227 Hz.	$f_1 = 11.333 - 10.88$ $f_2 = 10.88 - 10.2$ $f_2 - f_1$	360 n.mi.

Table II. Difference Frequencies and Lane Widths

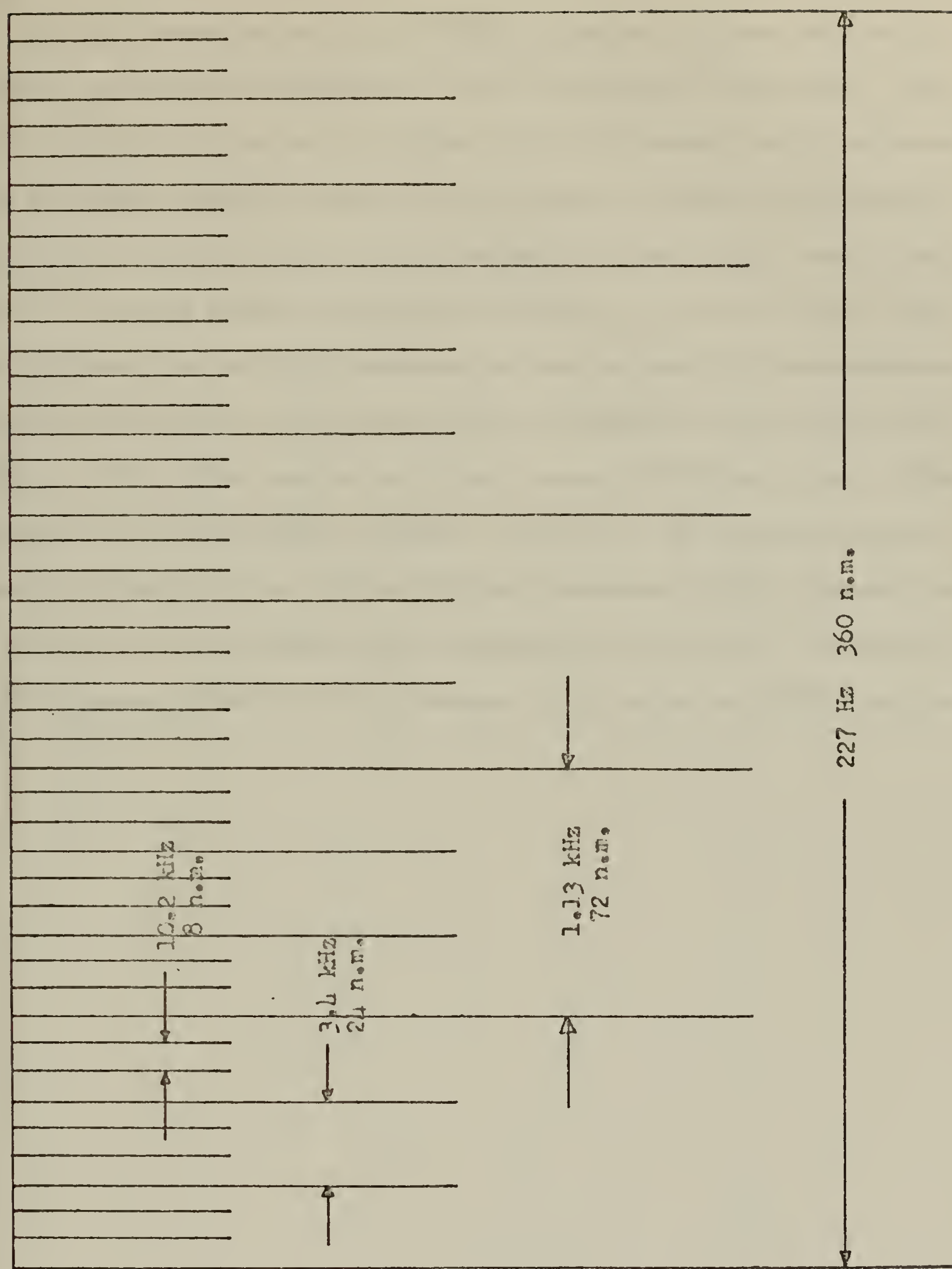

Figure 2 OMEGA Lane Substructure

B. OPLE TECHNIQUE

The VLF transmissions of the OMEGA navigation stations provide the signals for position information in the experimental OPLE system. The OPLE technique is the basis for GRAN. The OPLE concept was to retransmit the VLF OMEGA navigation signals from a remotely located user Platform Electronics Package (PEP), upon interrogation from an OPLE Control Center (OCC). The OPLE system is depicted in Figure 3. As can be seen, both the interrogation and PEP transmissions were relayed by a geosynchronous satellite transponder. The uplink (PEP to satellite) and downlink (Satellite to OCC) paths were at very high frequency (VHF) or higher. Other features of the OPLE system included a capability of converting local sensor information (i.e. air temperature, pressure, battery voltage, etc.) to digital form and relaying that information to the OCC. The received OMEGA signals at the OCC were processed to determine the PEP's location [6].

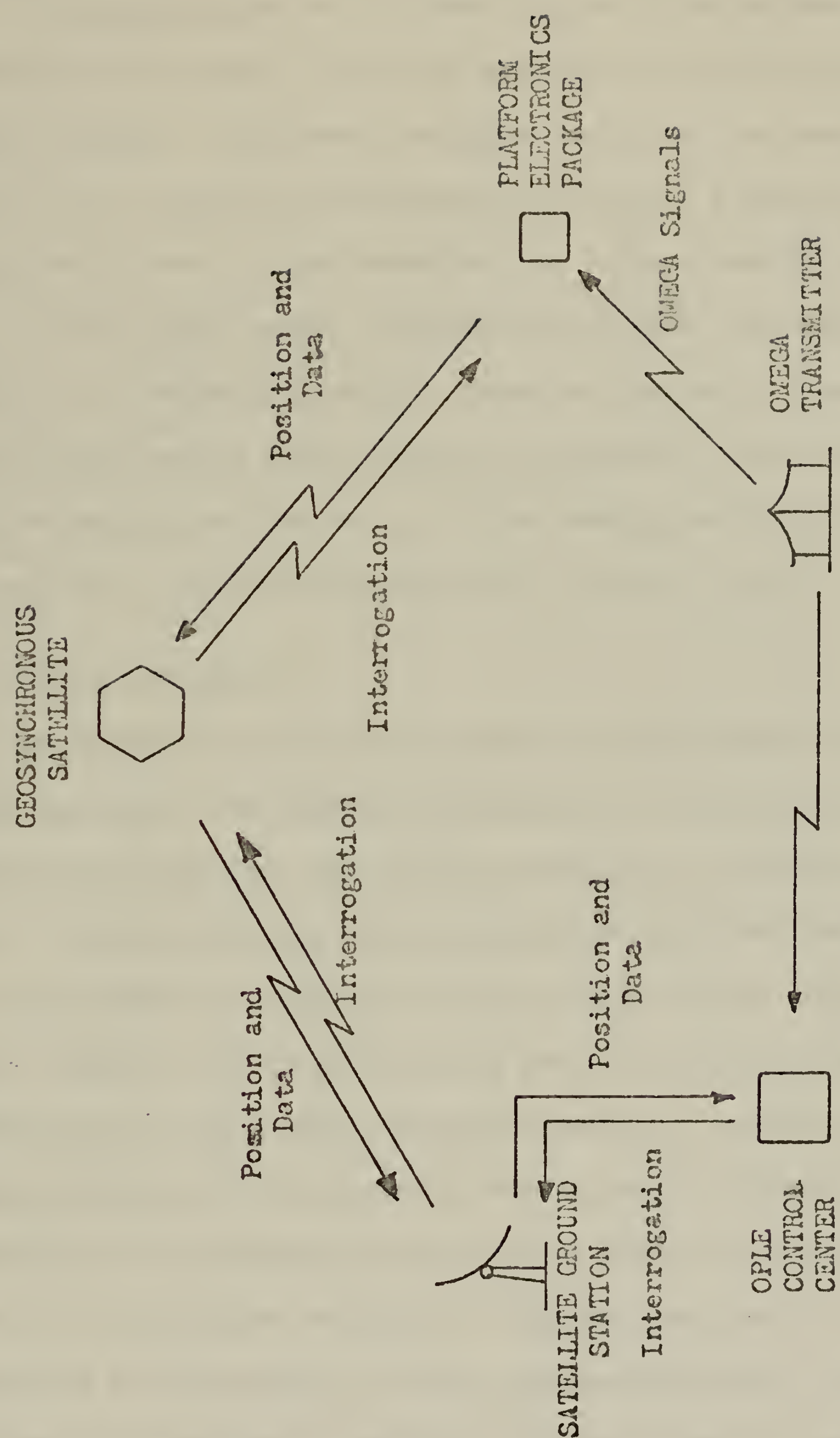

Figure 3 OPLE System

II. GLOBAL RESCUE ALARM NET (GRAN)

In the description of the OMEGA system it was pointed out that the hyperbolic LOPs repeat every half wavelength on the base line between OMEGA stations. For normal navigation this does not constitute a problem in lane identification because position for a starting point is known and a count of lane crossings can be kept manually or automatically. In the Global Rescue Alarm Net (GRAN) lane identification is not known nor is starting position. There are presently several methods for lane identification under analysis to determine which method or combination of methods will be used. In the ensuing analysis the assumption is made that lane identification will have been solved.

A. SYSTEM DESCRIPTION

The concept of the Global Rescue Alarm Net (GRAN) is similar to the OPLE technique. The GRAN system consists of a small Search and Rescue Communicator (SARCOM) unit which is analagous to the PEP of the OPLE system. The geosynchronous Search and Rescue Satellite (SARSAT) relay serves the same function in GRAN as it did in OPLE with one exception. The GRAN relay satellite has to provide only for a one-way link from the remote SARCOM unit to the central processing station. In GRAN the central processing station is the Search and Rescue Central (SARCEN). The SARCEN functions as a continuous monitor of the SAR band of frequencies and will lock onto any channel containing a SARCOM transmission. The bandwidth allocated to the system is 100 kHz located from 406 to 906.1 MHz. Forty channels are obtained by utilizing a folded spectrum technique to retransmit the OMEGA frequencies within a 2.5 kHz channel bandwidth. The

folded spectrum is shown in Figure 4. The complete SARCEN function includes monitoring, detection, lock-on and tracking, and signal processing of the SARCOM transmissions followed by outputting SARCOM unit identification, and near real-time position. The GRAN system is depicted in Figure 5.

B. GRAN SYSTEM FUNCTION

GRAN is intended to be a world-wide SAR system designed to give continuous global coverage. The activation of a SARCOM unit will be a random event in time and location, which can only be based on past and projected SAR statistics. Since the receiving antenna will be earth coverage and the system bandwidth is only 100 kHz, the system could easily be jammed from anywhere in the satellite's field of coverage. Jamming for a localized area would deprive system usage in the entire satellite coverage area. For example, suppose a satellite were positioned over the Pacific Ocean and a border conflict developed between two countries in North or South America. One side could jam the system to prevent usage in this localized area but as a result would prevent any usage in the whole Pacific area. Besides, a connotation that the GRAN system has a military flavor would make system implementation a political problem. The political aspects of the proposed GRAN system are not within the scope of this thesis.

1. Global Continuous Coverage

Figure 6 depicts the geometry involved in a circular satellite orbit. The satellite is orbiting the earth with a radius R. The satellite altitude is h. The central earth angle subtended by the observer at position P and the satellite subpoint (SSP) (point directly beneath the satellite) is θ. The satellite elevation angle is δ. The range from the observer to the satellite is S. The satellite antenna beamwidth is B.

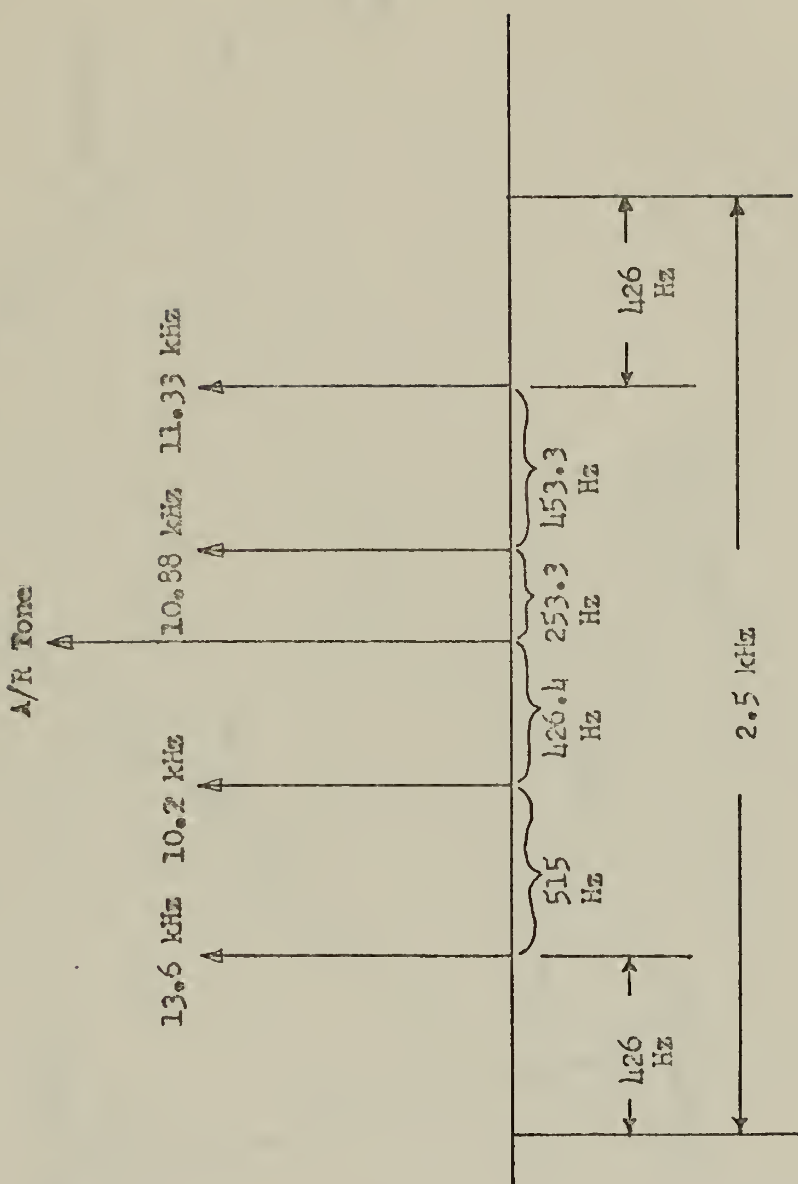

Figure 4 GRAN Folded Spectrum

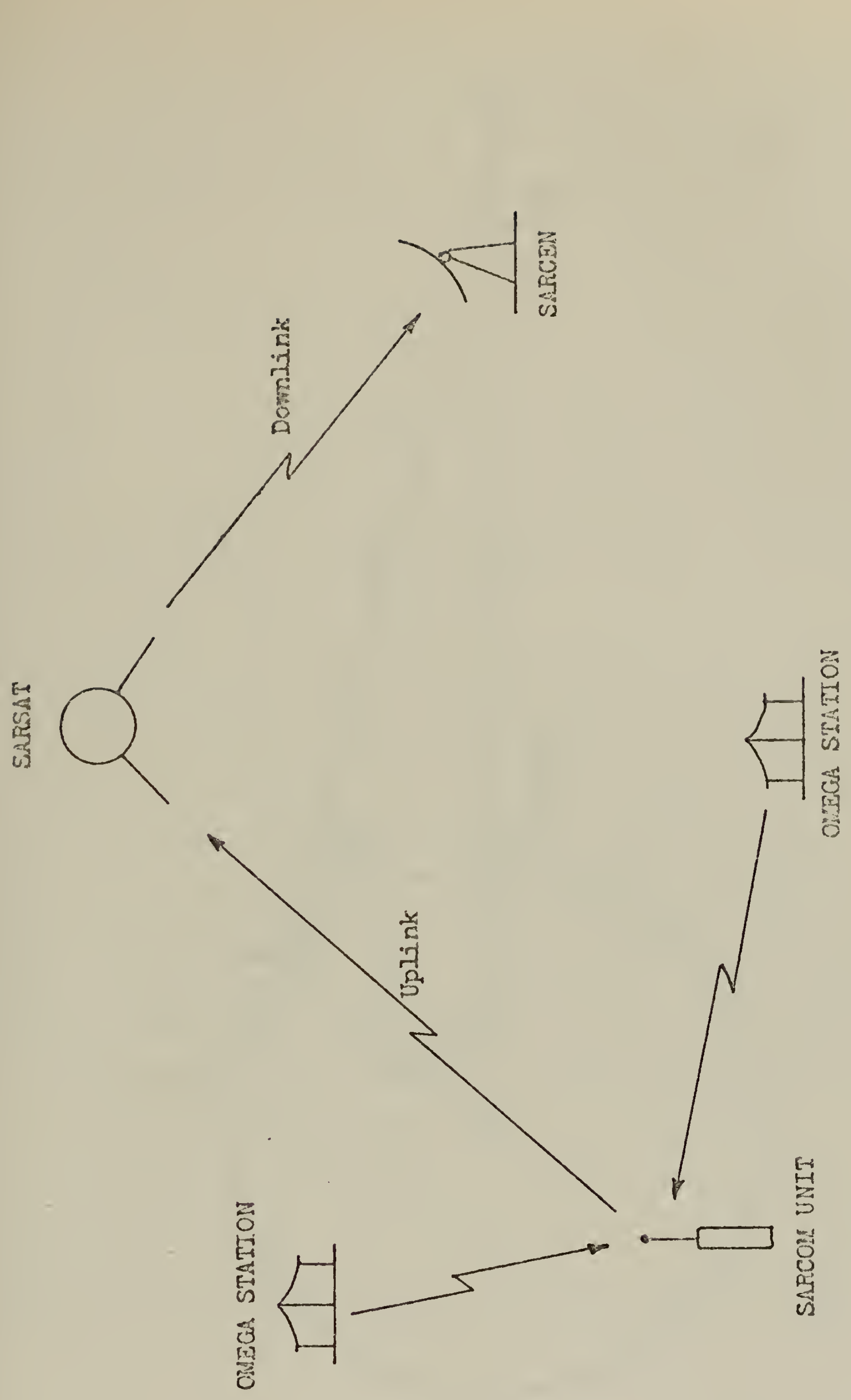

Figure 5 GRAN System

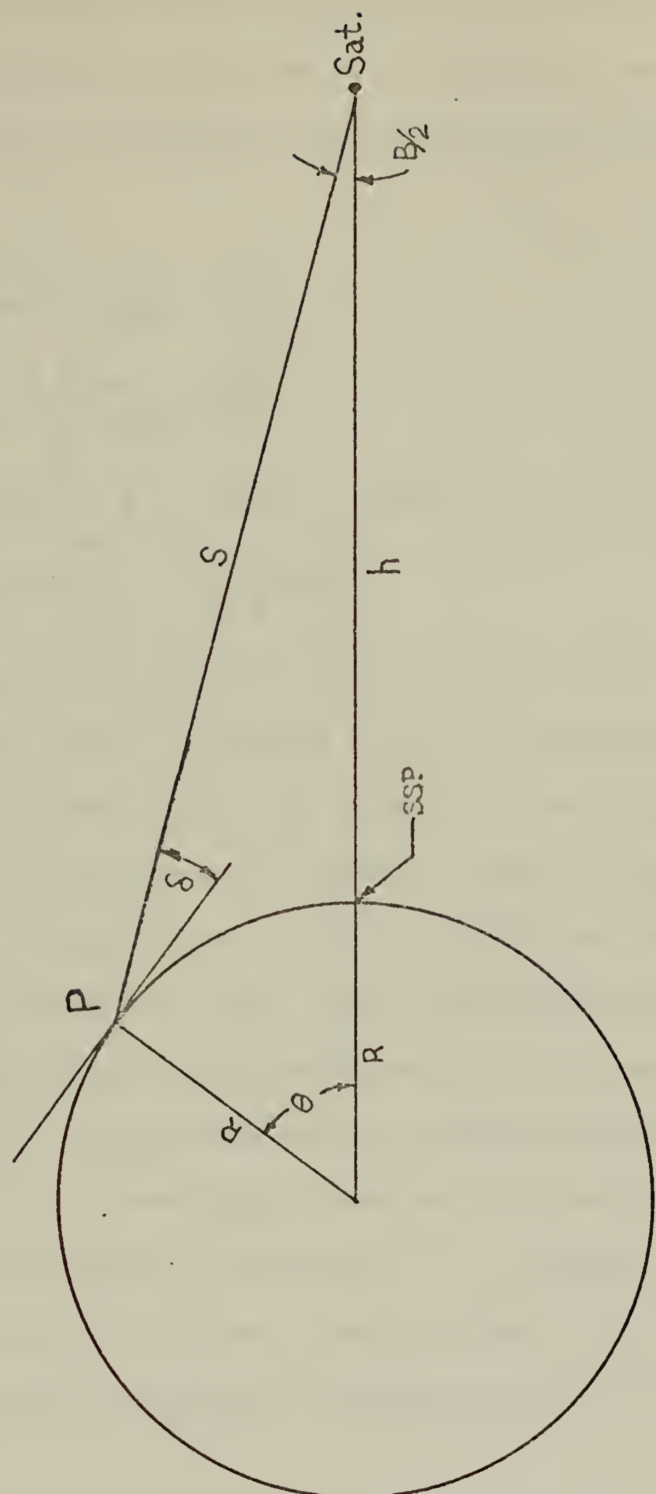

Figure 6 Satellite Circular Orbit Geometry

With these definitions the central earth angle will correspond to the maximum north and south latitudes of coverage for a satellite positioned over the equator. From geometric relationships the following equations are derived.

$$\theta = \left[\cos^{-1}\left(\frac{R}{R+h}\cos\delta\right)\right] - \delta \tag{1}$$

$$\delta = \tan^{-1}\left[\frac{\cos\theta - \frac{R}{R+h}}{\sin\theta}\right] \tag{2}$$

$$S = \left[(R+h)^2 + R^2 - 2(R+h)\,R\cos\theta\right]^{\frac{1}{2}} \tag{3}$$

$$B = \cos^{-1}\left[1 - 2\left(\frac{R\sin\theta}{S}\right)\right]^2 \tag{4}$$

For an example, take a geosynchronous satellite with h = 19,323 n.mi., R = 3440 n.mi., and $\delta = 0^\circ$, then $\theta = 81.3^\circ$. This would require, however, completely flat terrain with line of sight to the horizon always available. Therefore, this is not a realistic value for satellite elevation angle. If δ is taken to be a minimum of 7.5°, then the latitude of coverage is 73.8° north and south. With this central earth angle of 73.8° a single geosynchronous satellite covers only 72.1 percent of the area of a hemisphere. Further increase in altitude gives diminishing gains in coverage with increased path losses as shown in Table III. The increased losses would have to be made up with increased power at the SARCOM unit, a factor that would make the cost of the SARCOM unit increase rapidly, and would also require increased power at the SARSAT.

Satellite Altitude	Coverage as Percentage of Hemispheric Area	Increase in One Way Link Loss
Geosynchronous	72.1 %	0 (reference)
Twice Geosynchronous	77.8 %, increase of 5.7 %	-6 dB
Thrice Geosynchronous	79.3 %, increase of 7.2 %	-12 dB

Table III. Coverage and Link Loss Increase for Various Altitudes

From the area of coverage for a single satellite it is clear that two satellites cannot provide global coverage. Also, since any position of two satellites leaves regions located 180° apart yet to be covered, the addition of a third satellite still cannot provide global coverage either.

a. Three Satellite Coverage

The first phase of implementation of the GRAN system will probably be equatorial coverage. In this case maximum coverage with three geosynchronous satellites will be achieved with 120° spacing. These three satellites in the same equatorial orbit plane will give the coverage shown in Figure 7 with a minimum elevation angle of 7.5. The areas not covered are spherical triangles at the poles that remain fixed relative to the earth's surface.

b. Extension of System for Global Coverage

The first phase of GRAN implementation with equatorial satellites will leave polar regions uncovered as just described. Figure 8 shows the orbit plane of these equatorial satellites and the areas of non-coverage. The minimum number of satellites required to provide continuous coverage of these two regions is three satellites equally spaced in an inclined orbit plane. The inclination of the orbit plane must be at least 56° to insure minimum satellite elevation angle of 7.5° to all points. The inclination can be increased to as much as 90° with the

following considerations. Observe in Figure 9 that the ground track of a satellite in an inclined orbit plane will trace out a figure eight pattern about a point on the equator. Define this point as the equatorial longitude crossing. Figure 9 shows only the first six hours of the track. The remainder of the ground track is found from symmetry. At 56° inclination the satellites in the inclined plane will deviate from their equatorial longitude crossing by 15° west and 15° east while at the same time going 56° north and then 56° south. As the inclination angle is further increased, these deviations in longitude increase at a faster rate. The combination of longitude deviation and latitude deviation places more stringent requirements on the ground stations. Figure 10 is a plot of the minimum and maximum satellite elevation angles, as seen from the worst case position in the polar regions, against the orbit inclination of the polar coverage satellites. From the geographical poles the elevation angles are higher. To show the increased tracking capability required of the SARCEN stations, Figure 11 is a plot of delta longitude and delta latitude versus inclination angle of the polar coverage satellites. The delta latitude is just twice the orbit inclination angle while the delta longitude is the total longitude deviation and is divided equally each side of the equatorial longitude crossing.

C. USERS

What type of users can be expected, given the GRAN system is operational? As previously discussed, the GRAN system will not function in a jamming environment. Disregarding this environment, the users can be categorized into three major classes, (1) commercial, (2) private, and (3) peacetime military. Table IV depicts these three major classes of users with a breakdown of each class.

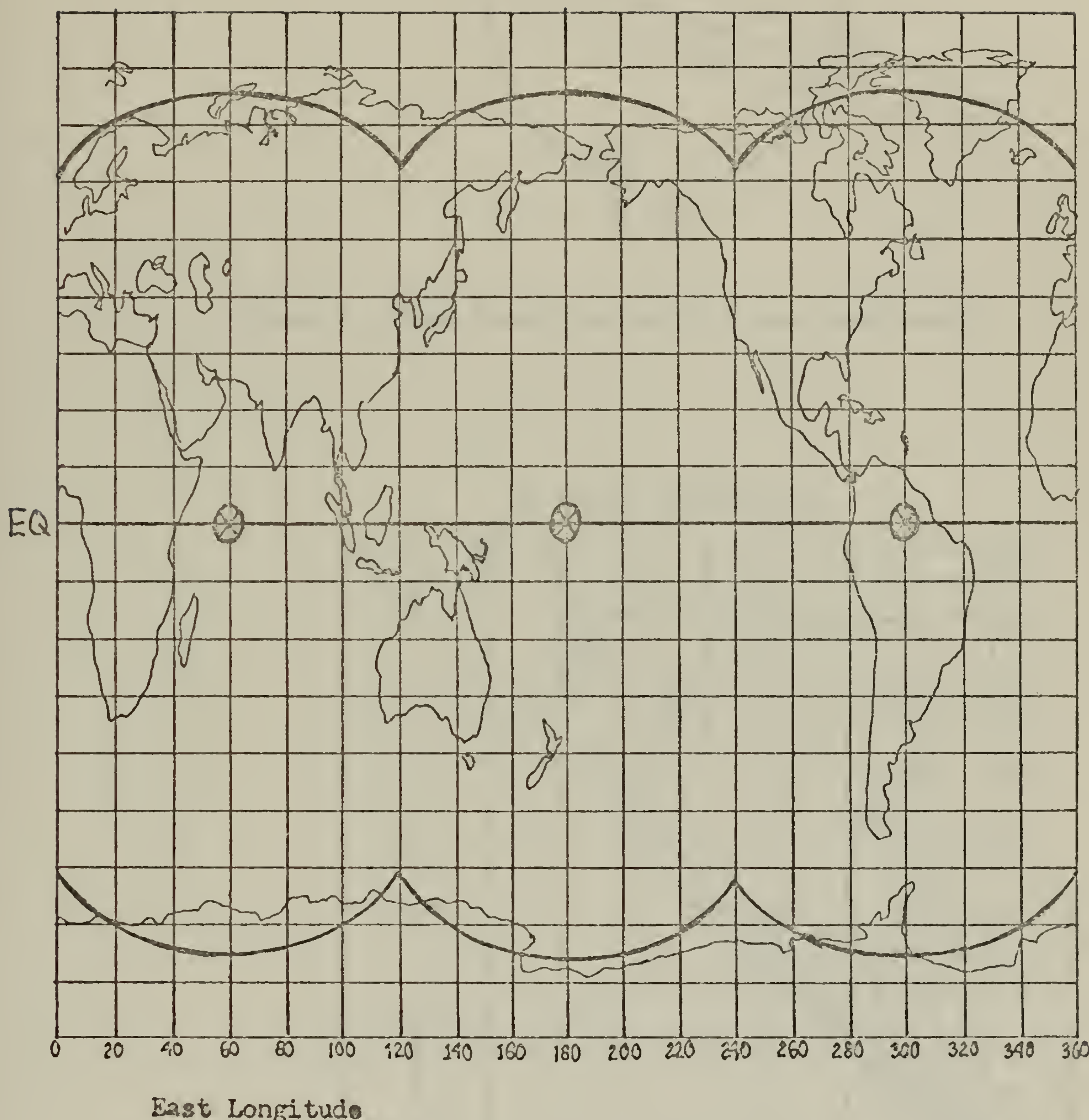

Figure 7 Three Satellite Coverage for Elevation Angle of 7.5 Degrees

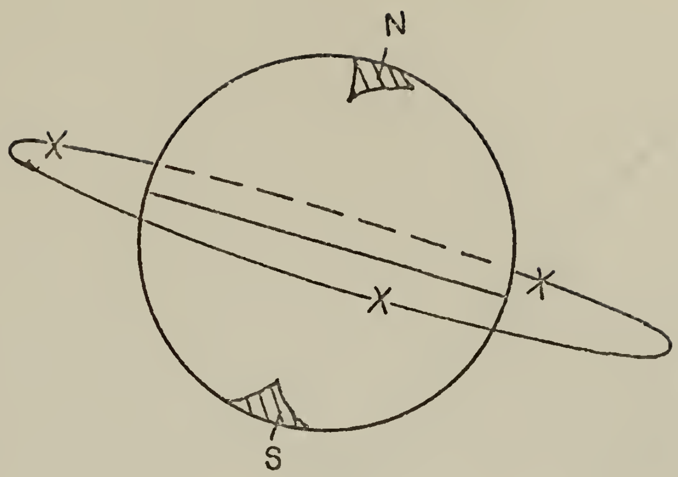

Figure 8 Three Satellite Orbit Plane (equatorial)

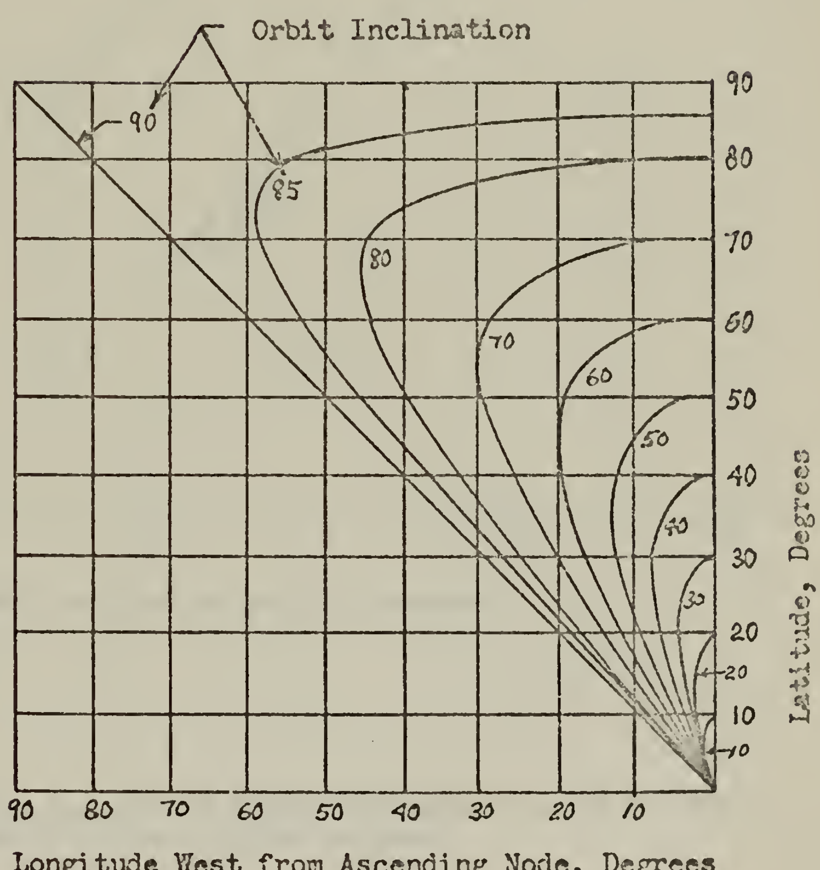

Figure 9 Ground Track of an Inclined Orbit

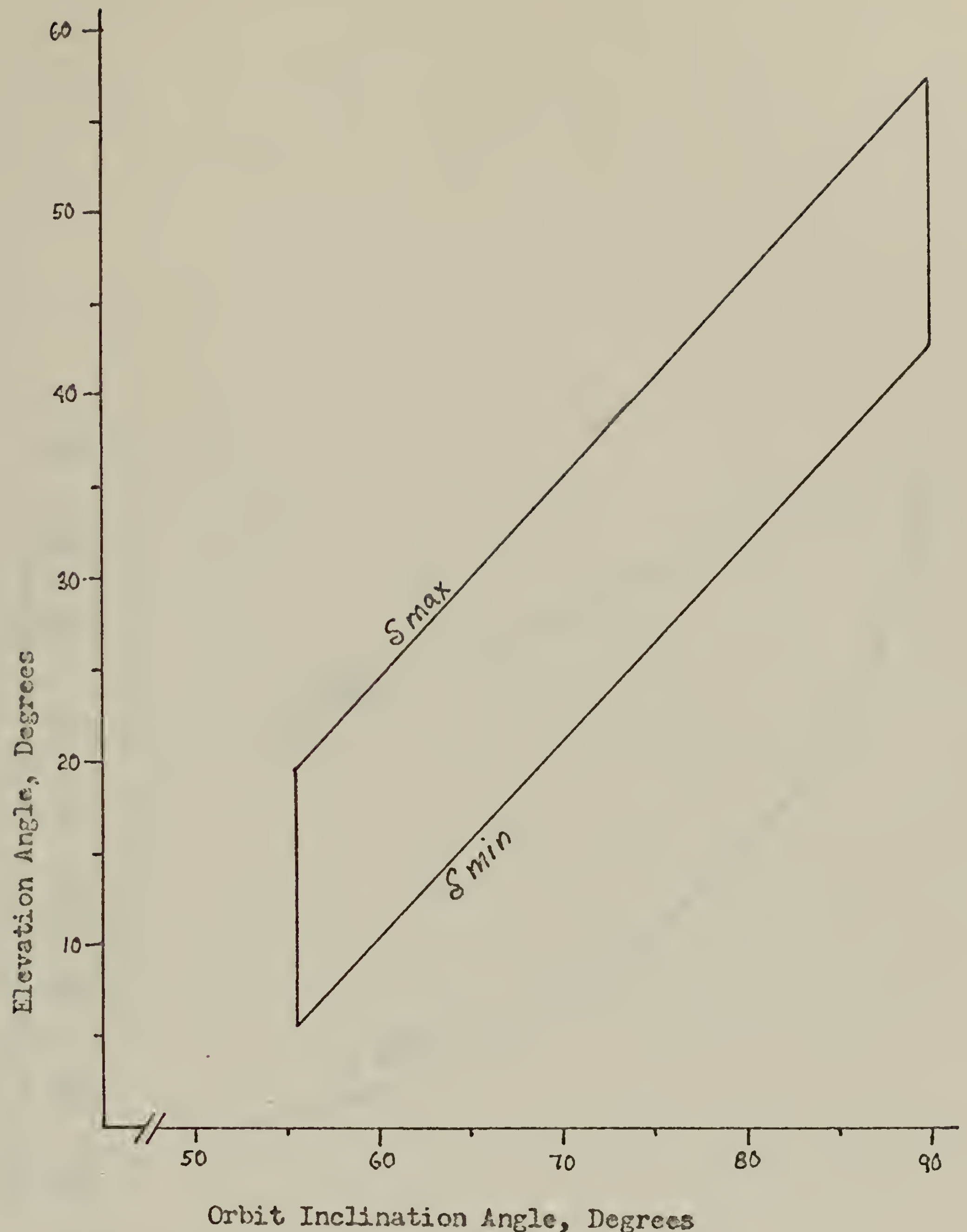

Figure 10 Elevation Angle vs. Orbit Plane Inclination Angle for Worst Case Position in Polar Regions

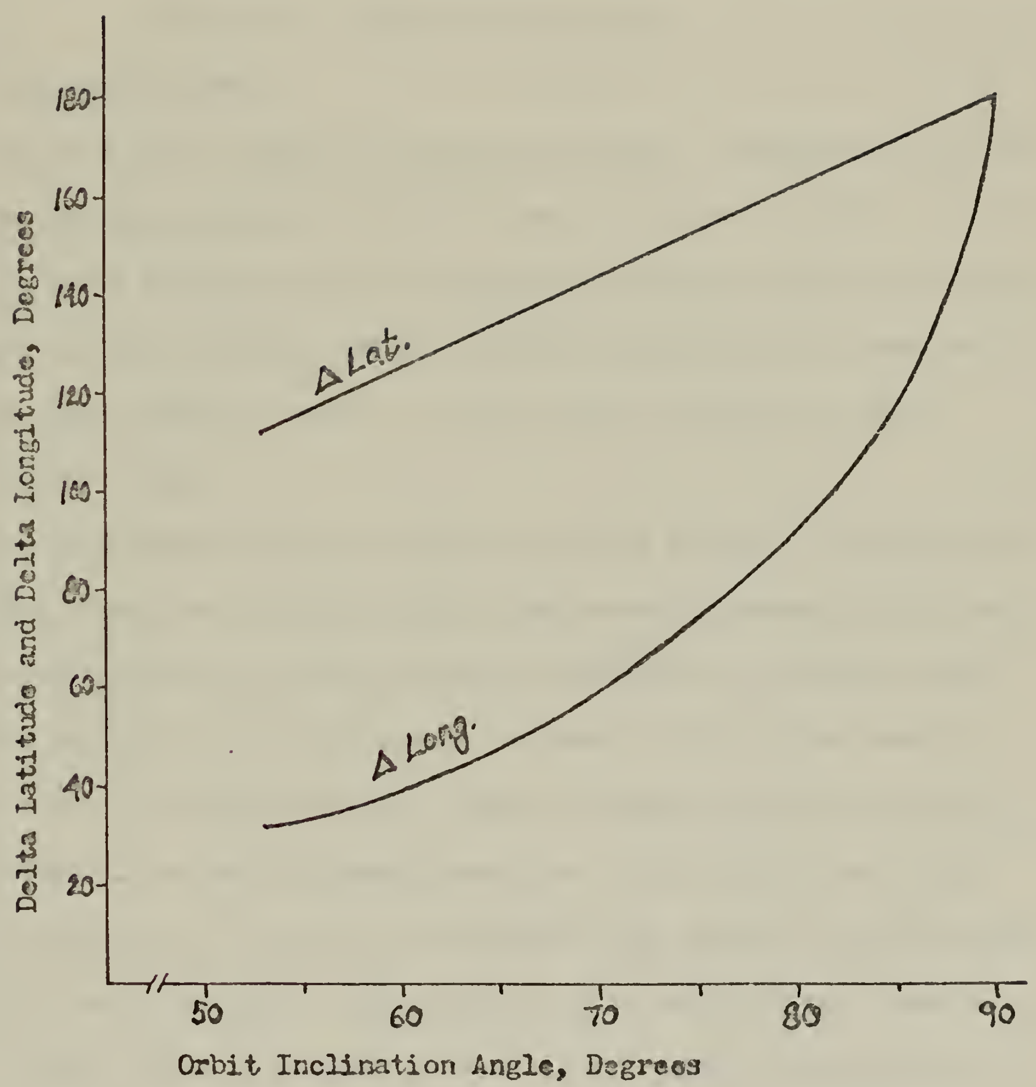

Figure 11 Delta Latitude and Delta Longitude vs. Inclination Angle

Commercial	Private	Peacetime Military
1. Aviation	1. Aviation	1. Avaition
2. Shipping	2. Boats	2. Ships
3. Land Vehicles	3. Miscellaneous	3. Land
a. Truck Lines		
b. Trains		
c. Buses		

Table IV. Possible GRAN Users

1. Commercial Users

In this class there are three main groups. Commercial aviation is made up of small airlines, charter lines, and global airlines. Commercial shipping includes all the ocean going vessels dealing with shipping cargo as well as cruise ships which deal primarily with services. Commercial land vehicles consist of truck lines, trains, and buses.

2. Private Users

In this class there are again three main groups. Pleasure boats which include ski boats, fishing boats, sailboats, houseboats, cruisers, etc. Private aviation is more generally referred to as civilian aviation. The third group, miscellaneous, is made up of all the small minorities such as mountain climbers, hikers, campers, hunters, motorcyclists and any other small groups associated with a leisure activity. As can be seen from the table, the different user groups could have been called air, water, and land, respectively. The geographical areas in which the users could be located extends to all parts of the glove and all types of terrain. This points out the suitability of a SAR system such as GRAN.

3. Military (peacetime)

The groups within this category are self-explanatory.

D. POSITION ERROR

1. OMEGA Error

OMEGA, as previously stated, uses very low frequencies (10-14 kHz) characterized by relatively stable propagation to very long distances (5000 - 8000 n.mi.). With the use of published skywave correction tables, the 10.2 kilo hertz signal provides navigation information on the order of 1 n.mi. accuracy within the lane of ambiguity. The combination of three LOPs provides an OMEGA fix accuracy of 1-2 n.mi. [7].

2. Phase Measurement

Appendix I contains the derivation for estimating the phase of a sinusoid of known frequency in white Gaussian noise. The received waveform is assumed to be

$$y(t) = A \sin(\omega t + \theta) + n(t) \tag{5}$$

where $t \in [0,T]$, T is the observation period, A is the amplitude of the OMEGA signal, and ω is the known frequency. Since the frequency ω is known, the maximum likelihood phase estimate, $\hat{\theta}$, of the phase angle of the received OMEGA signal is given by (6) [8].

$$\hat{\theta} = \tan^{-1} \frac{\int_0^T y(t) \cos \omega t \, d t}{\int_0^T y(t) \sin \omega t \, d t} \tag{6}$$

The quadrature components of the received signal have been observed over an integration time T (in our case, approximately one second at a time) then from these values $\hat{\theta}$ is determined. An OMEGA LOP is determined by taking the relative phase between two OMEGA stations. Therefore, since the local reference oscillator has a high stability over a short period of time, the phase of the reference oscillator will subtract out in

determining a LOP and hence is not included in (6). If, in fact, the values determined for the quadrature components are the same as the actual OMEGA signals, then $\hat{\theta}$ will be equal to θ. By defining the phase error ϕ as the difference between the phase estimate $\hat{\theta}$ and the actual phase θ, the mean squared phase error is from Appendix A.

$$E[\phi^2] = \frac{N_0}{2PT} \tag{7}$$

In (7) N_0 is the one-sided noise spectral density in watts/Hz, P is the OMEGA signal power in watts and T the integration time in seconds or 1/T is the bandwidth of the estimator. The OMEGA signal power and the noise power density N_0 must be measured at the same reference point.

3. <u>GRAN Error</u>

A single LOP is determined by measurement of the relative phase between two OMEGA stations. Thus

$$\hat{\theta}_1 - \hat{\theta}_2 = \theta_1 + \phi_1 - (\theta_2 + \phi_2)$$

$$\hat{\theta}_1 - \hat{\theta}_2 = (\theta_1 - \theta_2) + (\phi_1 - \phi_2)$$

where the numerical subscript refers to the OMEGA station and the symbols $\hat{\theta}$, ϕ, and θ are as just defined. Now

$$\Delta\hat{\theta} = \Delta\theta + \Delta\phi \tag{8}$$

Here the relative phase estimate is $\Delta\hat{\theta}$, the relative phase is $\Delta\theta$, and the relative phase error is $\Delta\phi$. The mean squared relative phase error then is

$$E[(\Delta\phi)^2] = E[\phi_1^2] - 2E[\phi_1\phi_2] + E[\phi_2^2]$$

But since the phase errors from separate stations are independent due to the randomness of the noise in successive one second intervals, the middle term equals zero. Hence

$$E[\Delta\phi^2] = \frac{N_0}{2P_1T_1} + \frac{N_0}{2P_2T_2}$$

But $T_1 \approx T_2 \approx T$, thus

$$E[\Delta\phi^2] = \frac{N_0}{2T} \quad \frac{1}{P_1} + \frac{1}{P_2}$$

The standard deviation of the relative phase error is

$$\sigma_{\Delta\phi} = \left[\frac{N_0/2}{T} \quad \left(\frac{1}{P_1} + \frac{1}{P_2} \right) \right]^{\frac{1}{2}}$$

The standard deviation of the measured phase error then in linear units is

$$D = \frac{\sigma_{\Delta\phi}}{2\pi} \cdot \frac{\lambda}{2} \tag{9}$$

where λ is the wavelength of the frequency measured in the desired linear units.

Equation (9) gives the linear error for one LOP. Defining fix error as D_F and assigning a numerical subscript to the LOP, the GRAN fix error is given by (10) [9].

$$D_F = \frac{1}{\sin\gamma} \sqrt{D_1^2 + D_2^2 + 2\rho\, D_1 D_2 \cos\gamma} \tag{10}$$

In (10) γ is the crossing angle for the LOPs, which is never less than 60°, and ρ is the correlation coefficient between the two LOPs. For separate pairs of stations ρ is small so the third term in the radical can be neglected. For two LOPs from three stations $\rho \approx \frac{1}{2}$ [9].

In the SARCOM signal format each station can be sampled 18 times. These separate sampling times correspond to independent samples and hence an integration improvement factor of $1/\sqrt{k}$ will be realized where k is the number of sampling intervals [10]. Also a reduction in D_F by approximately $\sqrt{3}$ can be achieved if all three OMEGA signal frequencies are used for a LOP.

E. DISTRIBUTION OF SARCOM CHANNELS

The allocated GRAN system bandwidth of 100 kHz allows for 40 channels 2.5 kHz wide using the folded spectrum technique as previously described. SAR statistics, users, and interference due to multiple access will be examined to determine some method of channel distribution. Finally probability of interference on one channel will be determined.

1. SAR Statistics

SAR statistics for each of the types of users as depicted in Table III are difficult to obtain. Three general groups maintain large scale statistics for which data is available [11 - 13]. Table V shows the figures for fiscal year 1971.

Air Force Rescue Headquarters	U.S. Coast Guard Headquarters	U.S. Navy Safety Center
267 cases (Fy'72)	48,894 cases	3,801 cases

Table V. SAR Statistics for Fiscal Year 1971

The 267 cases from Air Force Rescue Headquarters represent 218 civilian aircraft and 49 military aircraft. According to the Federal Aviation Administration, these figures cover civilian aviation for all of the United States. The 3,801 cases from the Navy Safety Center include Navy and Marine aviation in which Viet Nam data is included. Of the 48,894 cases from U.S. Coast Guard Headquarters, approximately 70 percent are recreational boats [11].

Table VI lists the U.S. Coast Guard Headquarters SAR figures for fiscal years 1967 through 1969. The following analysis is based on this data base representing 120,000 historical cases. A yearly increase of 6 percent was determined from which a projection of 50,000 cases for fiscal 1974 was made [14] and a figure of 70,800 for 1980 can be estimated.

Fiscal Year	SAR Cases
1967	37,728
1968	40,558
1969	42,281

Table VI. SAR Cases for Fiscal Year 1967-1969

Figures 12 through 14 and Table VII give SAR case distributions on the above described data base [14]. These distributions by month, day of the week, time of day, and USCG District represent a peak of 8 cases per hour in USCG District 3 [15] occurring during the summer months on weekend afternoons [14]. Figure 15 is a map of U.S. Coast Guard districts. The maximum rate of occurrence for the other USCG districts was 4 or less. It could be projected that the peak months and times for the Southern hemisphere would also occur during their vacation summer months although with the exception of Australia, little of the Southern hemisphere has pleasure craft. Sea temperature, air temperature, visibility, wind speed, etc. were analyzed with the result that only 4.5 percent of all SAR cases reported were caused by weather factors [14]. Correlation of these statistics with the fact that approximately 70 percent of SAR cases occur close in to shore in the pleasure boat group showed that over 60 percent of the reported SAR cases could have been handled without recourse to an electronic aid [16].

Under the assumption that the relatively close in pleasure boat group of U.S. Coast Guard cases is handled by already established SAR methods for localized recreational areas, then the primary function of GRAN comes to the foreground, that of serving the isolated distress case in the global community. The isolated distress case rate is approximately 30 percent of the total rate. This corresponds to an annual rate of

District	Number of Cases	Fraction
1	11,856	.098
2	593	.005
3	25,419	.211
5	10,175	.084
7	17,605	.146
8	10,061	.083
9	12,647	.105
11	6,962	.058
12	7,589	.063
13	11,850	.098
14	1,774	.015
17	2,729	.023

Table VII. Number of Incidents by U.S. Coast Guard District

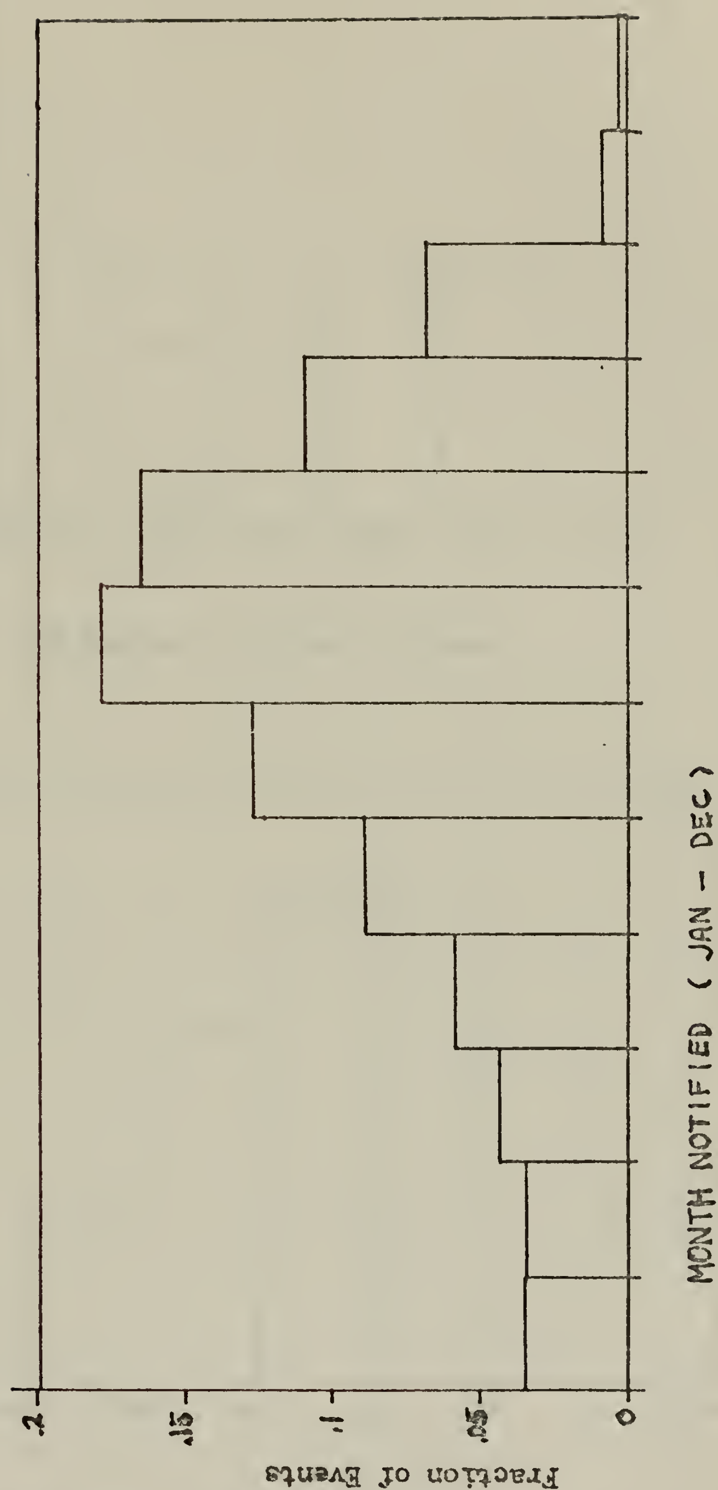

Figure 12 SAR Statistics by Month Notified

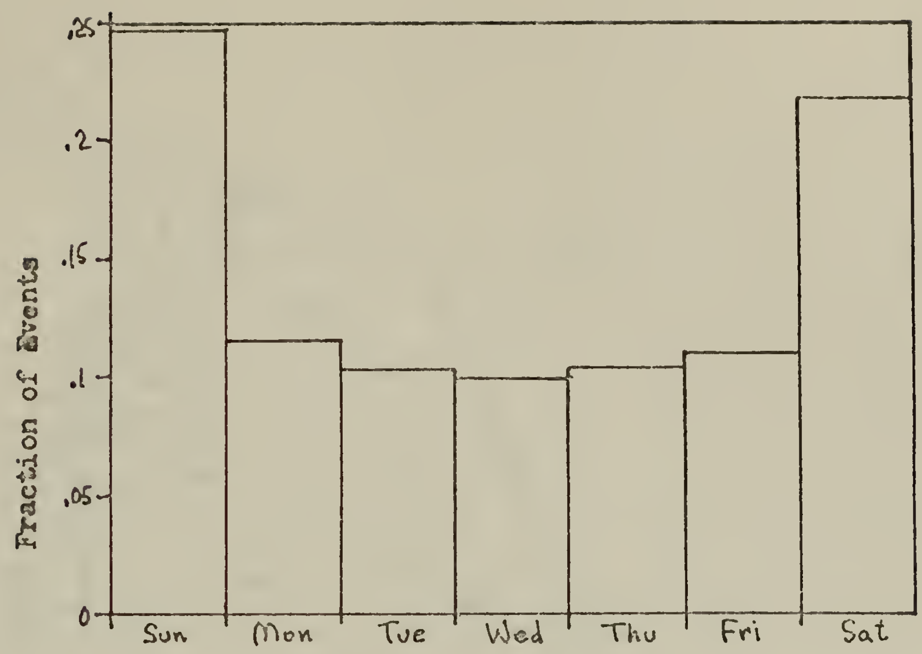

Figure 13 SAR Statistics by Day of Week

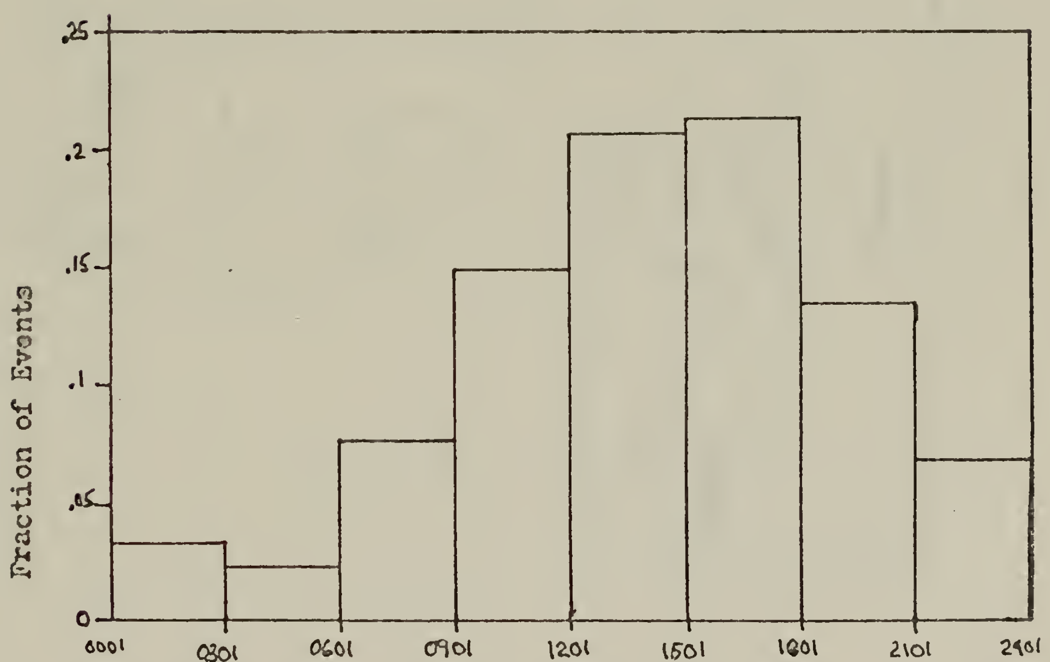

Figure 14 SAR Statistics by Time of Day

Figure 15 Map of U. S. Coast Guard Districts

15,000 isolated distress cases for fiscal 1974 and projects to 21,200 cases for fiscal 1980 at the rate of increase of 6 percent. It is highly unlikely that every distress case will also have a SARCOM unit. Thus make the assumption that only 80 percent of the distress cases will possess a SARCOM unit. This reduces the rate to 16,960. In most instances all normal means of communications are exhausted prior to using emergency methods. This is done in practice and is specified in laws governing aviation, etc. Therefore, the actual rate of usage that could be expected of GRAN would be even lower than the above figure. On this basis make the assumption that at least 50 percent of the time the distress cases possessing a SARCOM unit will be successful with some other means of communication and hence GRAN would not be used. That reduces the rate of 16,960 to 8,480.

The previous figure is representative of the United States. To give a realistic figure for the total area of coverage for one satellite would require SAR statistics from other countries. Make the assumption that the figure for the U.S. is at least twice the rate of South America, and that it is also four times the rate for Canada. This brings the rate up to 14,840 isolated SAR cases for a single satellite located over the mid longitude of the United States for fiscal year 1980.

2. <u>Multiple Access</u>

Define multiple access as the capability to transpond more than one SARCOM channel without intermodulation distortion. With this definition then consideration of the probability of SARCOM occurrences will determine multiple access capability.

Under the assumption that SARCOM transmissions occur at a constant rate, a Poisson distribution can be used to estimate the probability of

occurrences [17]. Defining λ as the rate of occurrence of transmissions and T the signalling time in seconds, the Poisson distribution is

$$\Pr(\text{m occurrences in T seconds}) = \frac{(\lambda T)^m \, e^{-\lambda T}}{m!} \tag{11}$$

By substituting 0 and 1 into (11) the following probability equations result.

$$\Pr(0) = d^{-\lambda T} \tag{12a}$$

$$\Pr(1) = \lambda T e^{-\lambda T} \tag{12b}$$

$$\Pr(\substack{2\text{ or}\\ \text{more}}) = 1 - [\Pr(0) + \Pr(1)] = 1 - (1 + \lambda T)e^{-\lambda T} \tag{12c}$$

Now by substituting into (12a), (12b), and (12c) the value obtained from the SAR statistics in the previous section multiple access can be analyzed. Using the figure of 14,840 isolated distress cases per year in 1980, this rate is equal to one case every 2,125 seconds. This is a value for the coverage of North and South America which also includes most of the Atlantic Ocean and about half of the Pacific Ocean. Evaluating the above equations using T equal to 198 seconds the length of time for a GRAN transmission it is found that 91.1 percent of the time there is no activity, 8.49 percent of the time there is only one SARCOM active, and 0.41 percent of the time there will be more than one SARCOM unit active. The conclusion then is that multiple access will not be a problem.

3. Probability of Interference

A slight modification to the previous section's work is necessary to evaluate interference. Define the probability of interference as the conditioned probability that one or more SARCOM transmissions will occur in the time interval T seconds on the same channel given that a SARCOM

unit is already transmitting there. Since the Poisson events are independent then this is just equal to the probability that one or more transmissions occur in the time interval T. The resulting equation is

$$\Pr(\text{int}) = \Pr(^{1\ \text{or}}_{\text{more}}) = 1 - \Pr(0)$$

$$\Pr(\text{int}) = 1 - e^{-\lambda T}$$

Now using the rate of occurrence from the previous section but assuming a uniform distribution over the SARCOM channels, the rate is 371 cases per channel per year. This is equal to one case every 85,000 seconds per channel. Substituting into the above equation and using 198 seconds for the signalling time T the Pr(int) is 0.233 percent. This probability of interference can be reduced further by a slight modification to the basic 198 second GRAN format. By incorporating multiple repeats of the basic format at random delays differing from SARCOM to SARCOM, the previously calculated probabilities will be smaller since now two SARCOM units in a given large area would be using the same delay.

There are inherent instabilities in the exact frequency location of the received SARCOM channel as will be seen later. That means then that if two SARCOM units came up on the same channel in the time interval T the OMEGA tones and their associated filter bandwidths might not necessarily overlap. For two interfering SARCOM units to exactly overlap would be highly improbable. Even when the OMEGA tones and their filter bandwidths did overlap, the SNR would degrade only by a factor of 2 or slightly more. The processing bandwidth for the OMEGA tones will be small compared to the OMEGA tone filter bandwidths. Hence, the OMEGA tones as received from the two different SARCOM units would only rarely be close enough to be within this processing bandwidth at the same time. By using tape recorders in the SARCEN station, the two interfering SARCOM

units can be tracked by manually locking onto the separate SARCOM transmissions when replaying the taped signals. Thus the conclusion then is that the probability of interference does not imply that that percentage of transmissions will be unprocessable. A further conclusion from this section is that a uniformly random distribution of SARCOM channels is recommended.

III. SARCOM

The Search and Rescue Communicator (SARCOM) unit is designed to be small, similar in size to a walkie-talkie, capable of handheld operation by a single switch with estimated cost around $200.00. The proposed design will be looked at here with emphasis on operation, antenna considerations, OMEGA frequency filters, oscillator instability and signal format and power division.

A. SIGNAL FORMAT AND POWER DIVISION

Since the initiation of the SARCOM unit is a random event in time, the full power of the SARCOM unit is first used to transmit the acquisition and reference tone (A/R). Figure 16 shows the GRAN signal format, where phase one is the alert phase in which the A/R tone is all that is transmitted. Phase two of the format is transmission of the SARCOM unit identification (I.D.) with A/R tone. Phase three is the OMEGA data phase in which the A/R tone is transmitted at reduced power with the remainder of the power being divided equally among the OMEGA frequency filters. Figure 17 is a simplified block diagram of the proposed SARCOM design. The first block after each OMEGA filter is a compression amplifier whose power output is a constant. In this manner the desired equal power in each OMEGA frequency and associated filter bandwidth is obtained. The final amplifier of the SARCOM unit is a linear amplifier and since the power division is obtained by separate compression amplifiers prior to the summing amplifier, intermodulation distortion is not a problem.

The OMEGA frequencies are translated in frequency by signals derived from the same source that generates the A/R tone. There will be

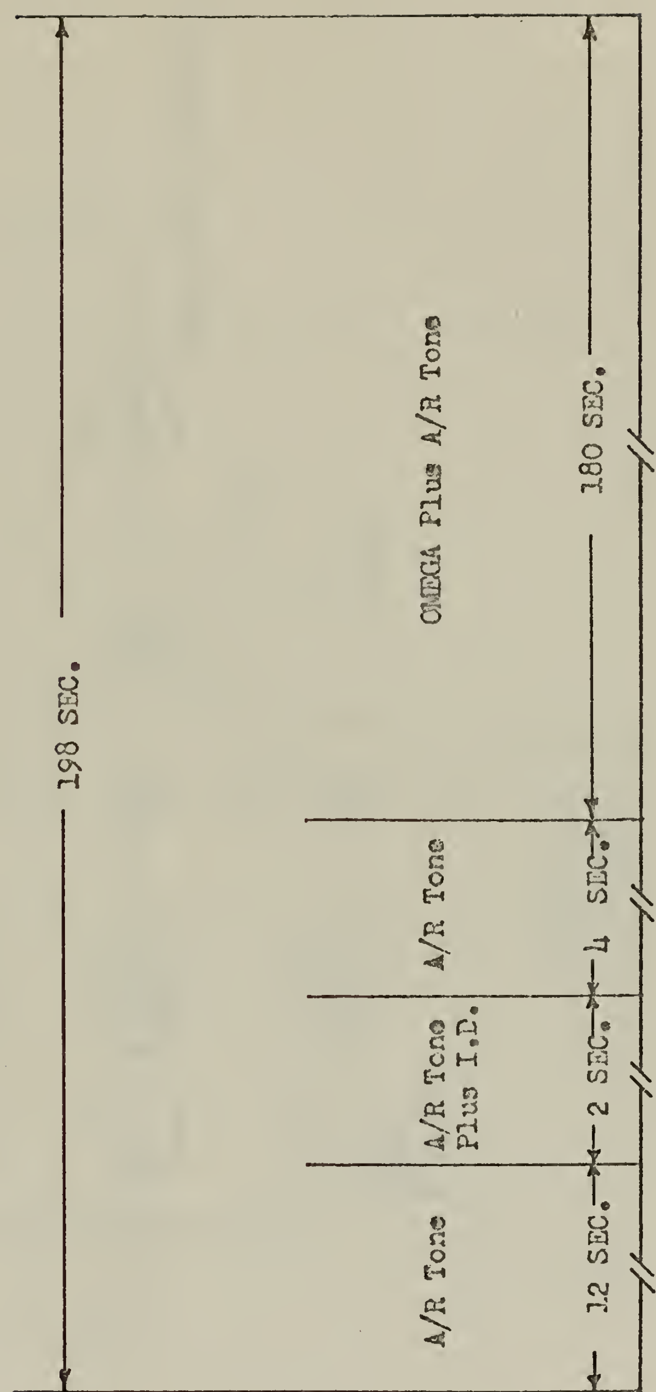

Figure 16 GRAN Signal Format

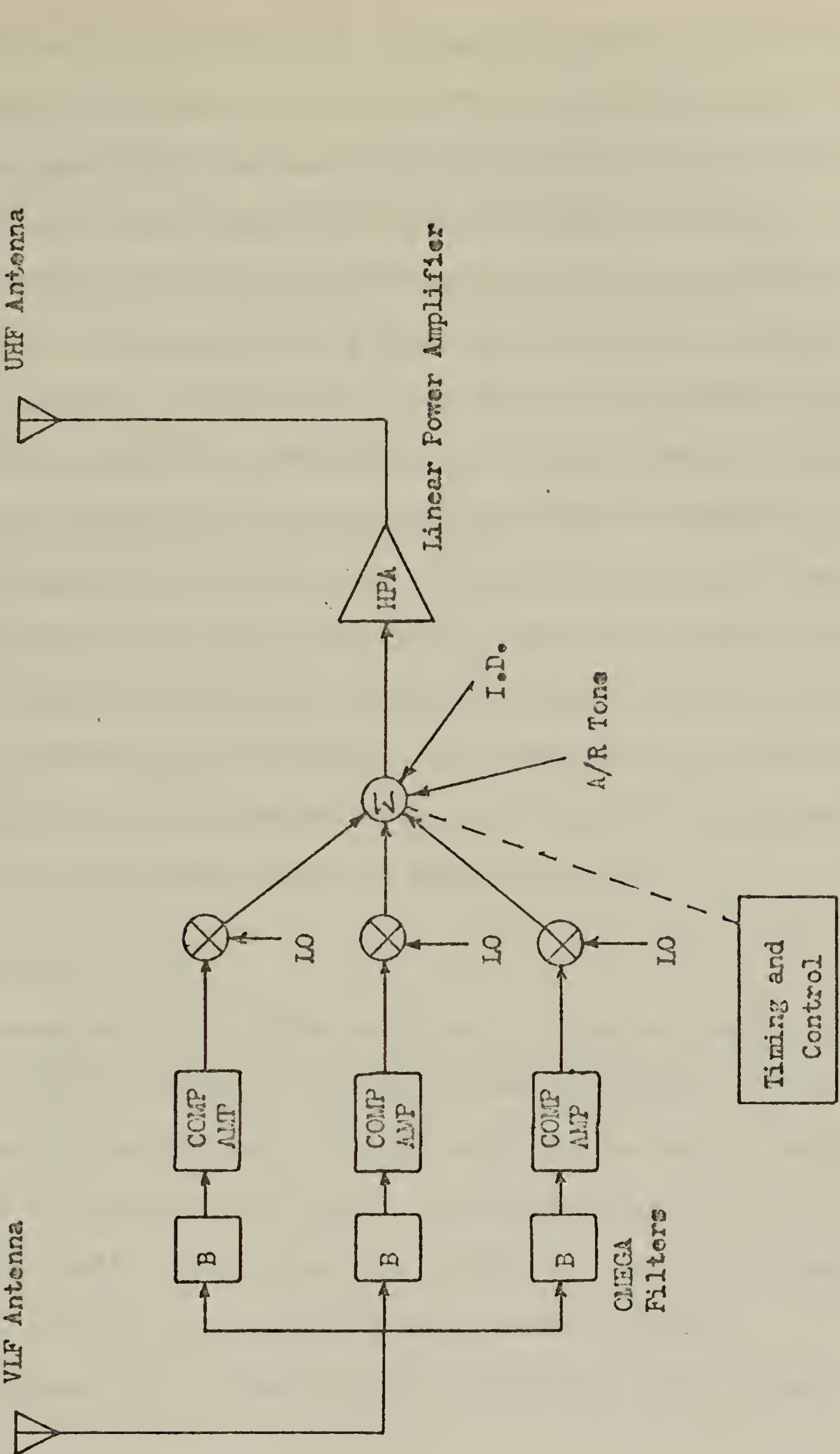

Figure 17 Simplified SARCOM Block Diagram

instabilities in the SARCOM local oscillator as well as the Search and Rescue Satellite (SARSAT). Since the OMEGA frequencies and A/R tone are related in spectrum by the same local oscillator, tracking of the A/R tone will eliminate these frequency shifts in the OMEGA frequencies. Additionally any doppler shifts due to SARCOM movement will be tracked out. Tracking can be accomplished by a phase-locked-loop (PLL) receiver.

Once lock-up is achieved on the A/R tone the PLL receiver reduces its bandwidth for tracking and effectively increases the SNR in the PLL. Hence, power reduction in the A/R tone can be made commensurate with the tracking bandwidth of the receiver. It has been shown that a reduction of from 4 watts in the alert phase to 0.5 watts in the OMEGA data phase of the A/R tone is sufficient to achieve 99 percent success rate for a tracking bandwidth of 10 hertz [18]. This power division equates to 10 percent A/R tone and 30 percent for each of three OMEGA tones for the proposed 5 watt power level during the OMEGA data mode.

B. OPERATION

The operation of the SARCOM unit should be kept as simple as possible. A single go/no-go operation type switch seems applicable. If the system is designed to function on a one-time basis, the tendency to activate the SARCOM unit in haste or the tendency to experiment will be low, especially if it will require refurbishing at a central station or if a penalty is imposed for intentional usage in a non-distress situation.

The antenna design should be highly reliable as well as easy to deploy.

C. ANTENNA CONSIDERATIONS

The field of view available to the SARCOM unit is essentially a hemisphere in which the position of the SARSAT is random due to the randomness of the SARCOM unit position. Thus an uplink antenna, which will be

at ultra-high frequency (UHF), ideally should have a hemispherical pattern. Since Faraday rotation occurs in transmitting a linear polarized signal through the ionosphere the SARCOM UHF antenna should be circularly polarized as should the SARSAT receiving antenna.

The OMEGA signals are vertically polarized at VLF frequencies. This implies that a vertical whip antenna on the SARCOM unit is required for OMEGA reception. Considering the wavelengths of the OMEGA frequencies this antenna will be a short dipole. One type of antenna possible could be the flexible steel flat antenna similar to a venetian blind slat. Two other possibilities are (1) a collapsible antenna similar to an automobile antenna or (2) a coiled spring flexible antenna.

A UHF antenna of the length required for the VLF whip antenna would give a pattern similar to a half-wave dipole which is far from being a hemispheric pattern. Therefore, it is impractical to consider one antenna for both receiving the VLF OMEGA frequencies and transmitting the UHF uplink. Separate antennas are required electrically though they could be connected mechanically.

In using the SARCOM unit consideration must be given to receiving the OMEGA signals as well as transmitting to the SARSAT. Reception of the vertically polarized OMEGA signals requires orienting the whip antenna vertical to the earth's surface. Transmission to the SARSAT requires orienting the UHF antenna pattern to project into the visible hemisphere overhead. If the SARCOM unit is designed so that these two orientations are accomplished by simply orienting the VLF whip then instructions for SARCOM operation are simplified.

D. OMEGA FREQUENCY FILTERS

Since each OMEGA signal is a single frequency of very high stability, i.e. one part in 10^{12}, it would appear an extremely narrow filter could be used on the SARCOM unit. The approximate ringing time of a fixed bandwidth filter, however, is crudely the reciprocal of the bandwidth. This means then that if the OMEGA filters are too narrow they will ring from noise spikes during the whole observation period of an OMEGA pulse. In Figure 1 it was shown that the transmission time and hence observation period of each OMEGA pulse is approximately one second. Hence if a ring time of one percent of the observation time were used as the criterion for bandwidth then the resulting filters would be 100 hertz. If a criterion of 10 percent were used, the resulting bandwidth would be 10 hertz for a gain of 10 dB in SNR over the 100 hertz filters.

Crystal filters are specified in the SARCOM design with accuracy of .1 percent and stability of .2 percent. At the highest OMEGA frequency of 13.6 kHz. this corresponds to about 40 hertz uncertainty in frequency. The conclusion then is that the filter bandwidth would become restrictive due to crystal limitations before ring time would be excessive. To obtain more accurate crystals would make the cost of the SARCOM unit exceed the desired limit.

As can be seen in Figure 17, the frequency translation of the OMEGA frequencies occurs after the filters. Therefore, the previously mentioned oscillator instability has no effect on the required filter bandwidths. However, in determining the exact frequency location of a given SARCOM channel at the SARCEN the oscillator instability plays an important role as does the doppler shift which will be seen later.

IV. SARSAT

In the previous chapter it was determined that the uplink antennas would be circularly polarized. Further considerations of the receiving antenna at the Search and Rescue Satellite (SARSAT) will be made in this chapter. The downlink antenna will be considered followed by linear and hard limiter amplifier considerations.

A. ANTENNA CONSIDERATIONS

The uplink antenna size and hence gain must be determined. For practical reasons it will be seen that a wider than earth coverage beam antenna should be used to facilitate deployment and to minimize physical support problems. For the downlink a frequency allocation has not yet been made. If the downlink frequency is high enough, then Faraday rotation through the ionosphere will be negligible. In this case linear polarized antennas could be used, although circular polarization would still be desirable because no polarization alignment at all would be needed.

1. Uplink Antenna

In chapter II the equations associated with a circular satellite orbit were stated. For the SARSAT receiving antenna the half-power beamwidth required for a minimum satellite elevation angle of 7.5° was determined to be 16.5°. Using nomographs from [19] that assume 54 percent efficiency the gain of a parabolic dish antenna with this beamwidth is 21.2 dB and has a diameter of 12 feet at the uplink frequency, 406 MHz. The transponded VLF noise from the SARCOM unit is the dominant factor in SNR as will be seen later. With this consideration then the beamwidth of

the receiving antenna can be increased with little affect on the SNR and allow the use of a smaller antenna.

Assume that a parabolic dish is used with efficiency of 54 percent. The uplink frequency is fixed at 406 MHz. Then by using the nomographs in reference [19] a plot of peak antenna gain versus antenna diameter can be generated. This graph is given in Figure 18. Further assume that the antenna pattern is Gaussian shaped, then the gain, G, as a function of angle, ϕ, off the beam center is

$$G(\phi) = G_0 e^{-k\left(\frac{\phi}{B}\right)^2} \tag{13}$$

where G_0 is the peak gain at the beam center, B is the -3 dB beamwidth, and the constant k is 2.773. From (13) and using the nomographs [19], the gain at ϕ equal to 8.25° can be determined and also plotted in Figure 18. This angle corresponds to the edge of coverage where the satellite elevation angle is 7.5°.

As previously shown, the -3 dB beamwidth of 16.5° is approximately a 12 foot diameter parabolic dish with a peak center gain of 21.2 dB. In Figure 18 it is seen that as the diameter is decreased from 12 feet, both the peak gain and edge gain decrease. It should also be noted that increasing the antenna diameter beyond approximately 13 feet that the edge gain now starts to decrease even though the peak gain is increasing. This corresponds to the gain pattern of a spot beam. Even though a 12 foot diameter antenna is slightly smaller than the antenna that would give maximum gain at the desired edge of coverage the difference in gain is small. Considering the problem associated with deploying and supporting a large diameter antenna it is more practical to use a slightly smaller than 12 foot antenna. Decreasing the antenna size to 9 feet gives an edge gain of approximately 17 dB and a center beam gain of approximately

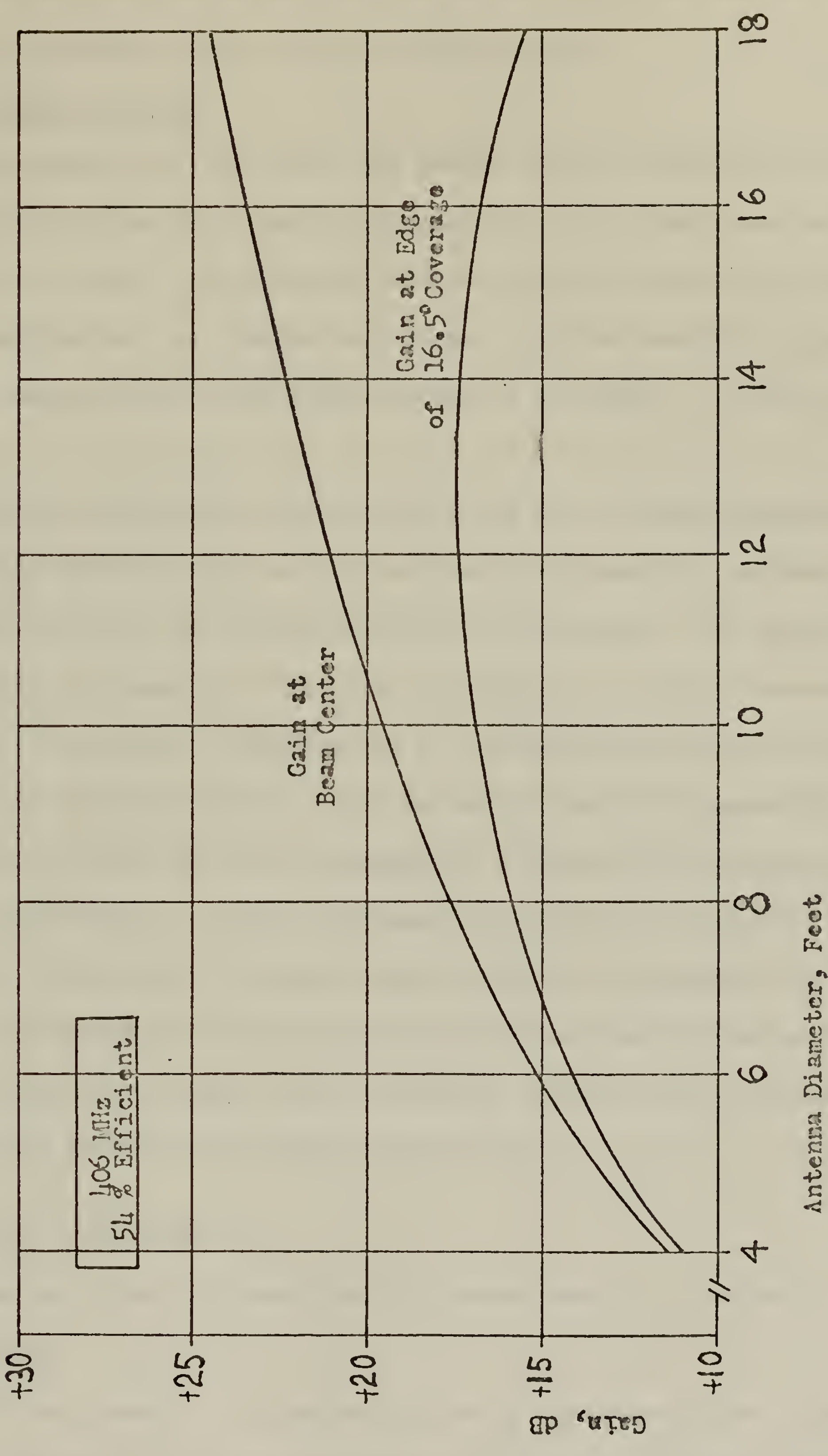

Figure 18 SARSAT Receiving Antenna Gain

19 dB. Another possible option would be to use a helix antenna as in the Tactical Communications Satellite (TACSAT) [20].

2. <u>Downlink Antenna</u>

The position of the Search and Rescue Central (SARCEN) and the SARSAT is known; therefore, the requirement to have an earth coverage antenna does not exist. As in the uplink, the size and hence gain of the downlink antenna must be determined. Assume that the downlink frequency is UHF but separated from the uplink frequency by 50 MHz, i.e. 406 ± 50 MHz.

Practical diplexers exist at these UHF frequencies; therefore, the receiving antenna could also be used as the transmitting antenna. There would, however, be practical limits to this usage. For example, as the frequency increases the beamwidth of a fixed size antenna decreases and its gain increases. Stabilization of the SARSAT would then determine how small the antenna beamwidth could become and hence the upper limit in frequency for this diplexer arrangement. Decreasing the frequency has the opposite effects, i.e. gain decreases and beamwidth increases. The actual gain of the SARSAT transmit antenna will be one parameter in determining the SARCEN G/T. If the downlink frequency were to be much higher than UHF, S band for example, then a separate antenna would be required. In this case a small horn antenna could be used.

B. AMPLIFIER CONSIDERATIONS

A linear amplifier and hard limiting transponder are considered.

1. <u>Linear</u>

The most important characteristic of a linear amplifier is that the output signal is an exact reproduction of the input signal except for amplitude. Two different signals fed into a linear amplifier at the same

time will give the same output for each signal as when the two signals are fed into the linear amplifier separately. A direct consequence of this is that SNR at the output of a linear amplifier is the same as the SNR at its input. Two types of linear amplifiers will be considered.

a. Straight Through Linear Amplifier

A straight through linear amplifier is one in which no intermediate frequency (IF) is employed. Any frequency translation is only that which is necessary to obtain the downlink frequency. An advantage of this type of linear amplifier would be in the simplicity of the design. A disadvantage, however, is in obtaining the necessary amplification at the incoming frequency of the uplink which is at UHF. Obtaining this amplification at UHF is more difficult and costly than at a lower frequency.

b. Intermediate Frequency Linear Amplifier

An IF linear amplifier is an amplifier that employs down conversion to an IF frequency for signal amplification. Then prior to driving the final amplifier upconversion to the downlink frequency is accomplished. An advantage in using this type of linear amplifier is the ease with which the amplification can be obtained. A disadvantage in using this type of amplifier, however, is the added complexity and expense in the SARSAT. The signal processing in both these amplifiers does not affect the SNR as previously stated so a trade off in reliability and expense would have to be made between these two amplifier techniques

In both the preceding linear amplifiers two problems would have to be resolved. They are (1) determination of bias point and (2) determination of amplifier gain. These two problems are interrelated. For example, specification of a bias point would then determine a maximum signal input for any given gain setting to prevent distortion and/or

saturation. It was previously determined that the probability of more than one channel being active would be .0041. Therefore, the bias point and gain setting could be determined from the maximum expected signal and transponded noise from one SARCOM unit. The total gain through the SARSAT is the combination of amplifier gain and antenna gain. In determining the desired gains a trade off will exist between gain through the SARSAT and ground station G/T as mentioned previously. This aspect will be examined in detail in a later chapter.

2. Hard Limiter

Processing a continuous wave signal through a hard limiter retains the signal phase information. Since the desired information in the OMEGA signals is phase then a hard limiter could also be used in the SARSAT. In a hard limiter SNR is affected in processing a signal. A SNR improvement of up to 3 dB can be obtained with greater than unity input SNR, but SNR degradation of as much as -1 dB can result from less than unity input SNR [21-23]. A major advantage in using a hard limiter amplifier is the reliability of a hard limiter versus a linear amplifier. Other significant advantages are simplicity of design and reduced cost.

It was shown in chapter II that the probability of more than one channel being active at one time is only 0.41 percent. The probability of only one channel active at one time is only 8.49 percent and that 91.1 percent of the time there would be no activity. These are figures projected to 1980. Since 91.1 percent of the time there is no activity, the normal mode of operation for a SARSAT will be transponded noise with one channel active only 8.49 percent of the time. From this it can be concluded that multiple access will not be a problem, nor will intermodulation be a problem. Further it can be shown that for interfering SARCOM channels, a rare occurrence (probability of .00233), the intermodulation

distortion would appear as a noise source far beneath the transponded VLF noise. Based on this analysis of amplifier considerations it is concluded that a hard limiting transponder is the best solution for the SARSAT amplifier.

V. SARCEN

In a previous chapter it was determined that a system of three equatorial geosynchronous satellites and three inclined plane satellites could provide the desired continuous global coverage for the GRAN system. In this chapter one of the topics to be covered is how many and where the Search and Rescus Central (SARCEN) stations have to be located to monitor the SARSAT system. Other points to be examined are antenna considerations, monitoring, and SARCOM tracking.

A. ANTENNA CONSIDERATIONS

The signals to be received at a SARCEN are from circular polarized antennas if the downlink frequency is in the UHF range. If the downlink frequency were to be high enough Faraday rotation through the ionosphere is negligible and in this case a linear polarized antenna might be used as previously discussed. The positions of the SARSATs are fixed relative to the earth for the equatorial satellites and hence once an antenna is alligned the need for tracking corrections can be performed by hand since the beamwidth will be relatively large. In the case of the inclined orbit satellites a tracking antenna would be required with tracking capability commensurate with orbit inclination and SARCEN position as was shown in section II.B.1.b.

For a fixed antenna size on the SARSAT and a specified downlink frequency there is an associated path loss. The gain can be made up in two places to overcome these losses. They are the SARSAT power amplifier and downlink antenna gain and the SARCEN receiving antenna gain and front end noise temperature. Thus a trade-off exists between the SARCEN station's

G/T and the SARSAT's gains. This trade-off will be examined in more detail later.

B. NUMBER AND LOCATIONS OF SARCENS

The first phase of GRAN implementation will most likely be three equatorial geosynchronous satellites as described in chapter II. A SARCEN located within 73.8° of a satellite subpoint will have the minimum elevation angle to the satellite of 7.5°. Observe in Figure 19 that this describes overlapping ranges along the equator where a single SARCEN can observe two satellites. The range of overlap is 27.6° on the equator. Two SARCEN stations could monitor this three satellite system by placing one SARCEN station in one of these three overlapping areas in Figure 19 and the second SARCEN anywhere within view of the third SARSAT. The actual geographical positions would be a political problem. Placement of the SARCEN stations would then determine at what longitudes the SARSATs would be placed. For example, suppose two of the three geosynchronous satellites were located over the Pacific and Atlantic Oceans. A SARCEN station could be positioned in Texas at the ground station for the experimental OPLE system. The overlap for observing these two satellites allows the three satellite system to rotate east or west 27.6°. This defines a longitude span of 202.8° along the equator from which the third SARSAT could be monitored. This would allow the second SARCEN station to be positioned almost anywhere in the free world countries from Europe to Australia.

It was shown in chapter II that the minimum inclination angle for the polar coverage satellites is 56°. Refer to Figure 11 of chapter II. This figure gives a delta latitude of 112° and a delta longitude of 32° for an inclination angle of 56°. In Figure 9 the maximum delta longitude for

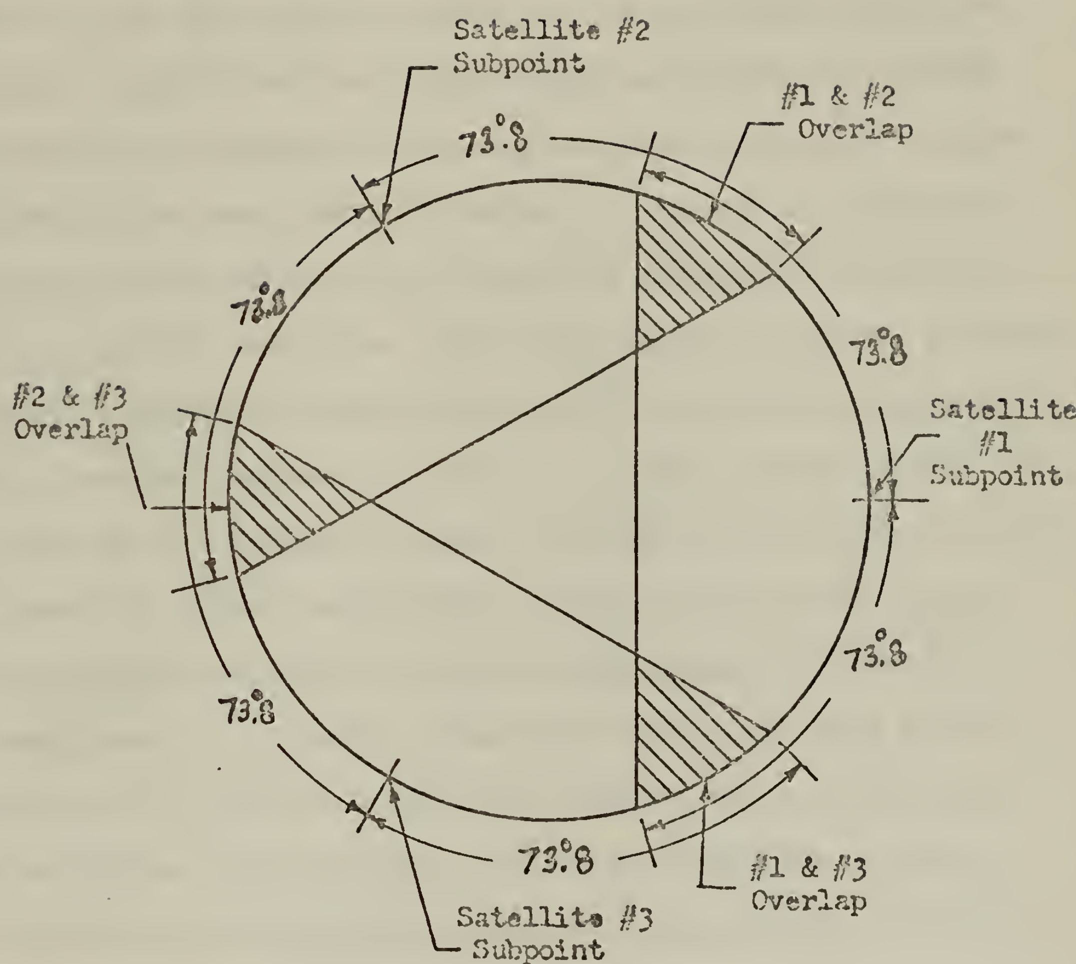

Figure 19 Equatorial Satellite Overlap

this inclination occurs when the satellite is 38° off the equator. At this position the equatorial span of one SARSAT can be shown geometrically to be only 128°. When the satellites are at the maximum delta latitude of 56° off the equator, it can be shown geometrically that the equatorial span is only 111°. This eliminates the possibility of two SARCEN stations being able to monitor this six satellite system. A minimum of three SARCEN stations would have to be used. The locations of the SARCEN stations could then be placed so that each station would see one equatorial satellite and one inclined plane satellite. The SARCEN stations could also be placed in the three overlapping regions in Figure 19. This would allow each SARCEN to monitor two equatorial satellites and one inclined plane satellite which could be placed at the midpoints between the equatorial satellites. This would allow the tracking antennas to always have a minimum elevation angle of 56°. The minimum elevation angle would, however, decrease by the north or south latitude of the ground station up to a maximum allowable latitude of 17.8° north or south. This arrangement of SARSATs and SARCENs is shown in Figure 20. For an example of geographical locations, pick one SARCEN station in British Guiana, South America or Barbados. This then defines two areas 55.2° in longitude and 17.8° south latitude to 17.8° north latitude in which the other two satellites could be placed. This would then allow a second SARCEN to be located in the Caroline, Line, Phoenix, or Marshal Islands with a third SARCEN station located in the Amirante, Seychelles or Chagos Islands.

C. MONITORING

The conclusion has already been made that the normal mode of operation of a given SARSAT would be transponded noise. A scheme of scanning

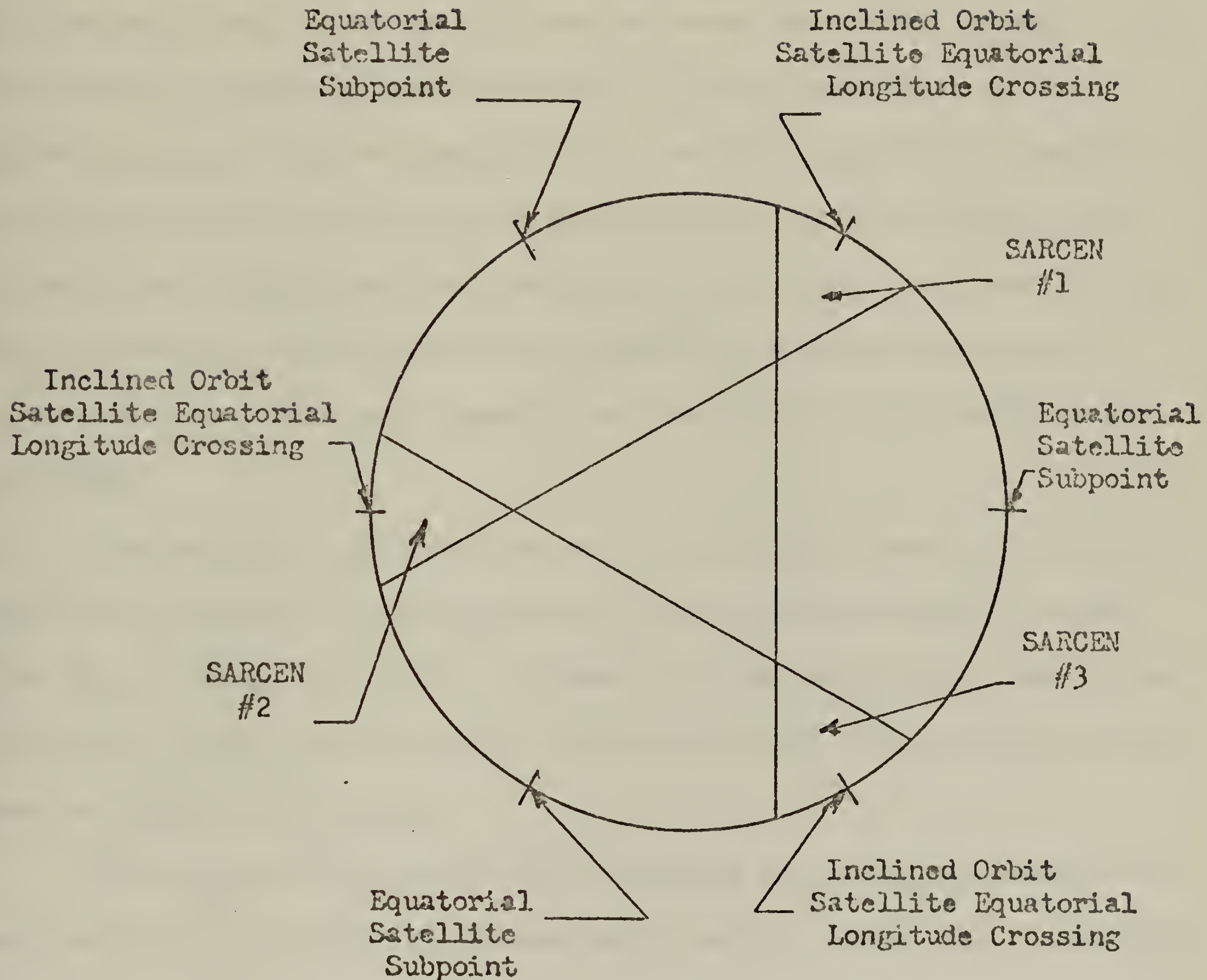

Figure 20 Six Satellite Three SARCEN Pattern

the allocated SAR band or continuous monitoring of all 40 channels must be employed. The whole system by necessity will be computer controlled and processed.

1. Uncertainty of A/R Tone

It was mentioned in chapter III that the SARCOM local oscillator instability had no effect on the OMEGA filter bandwidths. In receiving the SARCOM channel at the SARCEN there exists an uncertainty in the exact frequency location of the A/R tone and hence the SARCOM channel. This uncertainty is generated by three things, (1) the instability of the SARCOM oscillator, (2) the instability of the SARSAT oscillator, and (3) the doppler shifts that occur from SARCOM and/or SARSAT movement. Due to design cost limitations the instability of the local oscillator in the SARCOM units will be dominant over the SARSAT oscillator instability. Doppler frequency will vary depending on the motions of the SARCOM unit and SARSAT.

The design of the SARCOM calls for a 1.5 ppm accuracy in frequency. Define the bandwidth of uncertainty due to the oscillator drift as Δf_0. Then Δf_0 is simply $2(1.5)10^{-6} \times f$ where f is the uplink frequency. Take the highest channel which would be approximately 406.1 Mega hertz and the resultant Δf_0 is 1218 hertz.

Now define the bandwidth of uncertainty due to doppler shifts as Δf_D and the total bandwidth of uncertainty as Δf. Table VIII then gives the total bandwidth of uncertainty for several platform movements which is just the sum of Δf_0 and Δf_D.

Platform	Relative Velocity	Δf_D	$\Delta f = \Delta f_0 + \Delta f_D$
Fixed	0	0	1218 Hz.
Ship	15 knots	20.9 Hz.	1238.9 Hz.
Ship	30 knots	41.8 Hz.	1259.8 Hz.
Aircraft	150 knots	209 Hz.	1427 Hz.
Aircraft	300 knots	418 Hz.	1636 Hz.
Aircraft	600 knots	936 Hz.	2154 Hz.

Table VIII. Bandwidth of Uncertainty of A/R Tone

The previous table lists bandwidths of uncertainty which include aircraft at speeds up to 600 knots. Since most aircraft at altitude are within other communications capabilities, their usage is highly improbable. The projected probable movement for a platform would be a ship at sea at an average speed of 15 knots or a liferaft adrift at sea moving much slower.

Even though the assumption has been made that the SARCOM oscillator instability would dominate over the SARSAT oscillator instability, should the latter become a problem it could easily be tracked out by relaying a pilot tone through the SARSAT in the SAR band fringes.

2. Tape Recorders

Given that a particular monitoring scheme is determined, a system of tape recorders would be useful for the following reasons.

a. Recording and storage of pertinent received data, i.e. SARCOM call ups, action taken, system status, etc.

b. Recording signals in process for recall and reprocessing in case of loss of tracking by the PLL receiver.

c. Recording interferring signals for separation in a manual select mode of processing.

d. Recording of channels requiring a delay time for processing as in the case of exceeding the number of PLL receivers for multiple channel processing.

3. Spectrum Analyzer

A spectrum analyzer approach might be considered as the monitoring scheme. In any scheme chosen a basic requirement for SNR for detection must be met. From Appendix B the SNR in a 1 hertz bandwidth required for detection is

$$(S/N)_{1\ Hz} = k\sqrt{B/t} \tag{14}$$

In (14) k = 10 from empirical determinations [24], B = IF bandwidth, and t is the averaging time after the detector. This can be related to the sweep rate, R, in a spectrum analyzer as follows. The signal if present would remain in the spectrum analyzer filter bandwidth for a time period T = B/R seconds. Ideally the averaging time t should be equal to the time the signal spends in the filter bandwidth, T seconds, so substituting for t in (14) the result is

$$(S/N)_{1\ Hz} = k\sqrt{R} \tag{15}$$

In (15) it is seen that as scan rate is increased so must $(S/N)_{1\ Hz}$ since the signal remains in the spectrum analyzer IF bandwidth for a shorter period of time. For example, assume a scan rate of 100 kilo hertz every 4 seconds. Using the empirical value of 10 for k the resulting SNR required is 32 dB. Another factor comes into play, however, and that is the response time of the IF filter or what is more commonly called "rise time", T_r. Typically $T_r = 1/B$ is used as a rule of thumb. This requires that the signal remain in the IF bandwidth B for at least T_r seconds to be detected. So setting T, the time in the filter bandwidth, to be greater than or equal to T_r, the resulting scan rate must be less than or equal

to $(B)^2$. Therefore if the required frequency resolution for detection is 50 hertz then the IF bandwidth B is 50 hertz and the resultant scan rate has to be less than or equal to 2500 hertz/second. At this scan rate it would take 40 seconds for the spectrum analyzer to scan the 100 kilo hertz SAR band. At this scan rate the time spent in the neighborhood of one SAR channel would only be 5.55 percent, and based on the bandwidth of uncertainty for the A/R tone the time spent in this bandwidth would only be 1.24 percent.

4. Channel Filters

Another approach to the monitoring problem would be the use of separate channel filters. Since the bandwidth of uncertainty for the A/R tone is approximately 1240 hertz, this would imply 40 individual spectrum analyzers. As before, for a 50 hertz resolution the scan rate must be less than or equal to 2500 hertz per second. This would yield a scan time of about 500 milliseconds. Since the A/R tone is broadcast at the maximum power of the SARCOM unit for 12 seconds then this approach would assure detection provided the minimum required SNR is present.

5. Fast Fourier Transform (FFT)

A FFT scheme utilizing a near real time special purpose digital computer is a third approach to the monitoring scheme. The FFT is a computational tool which facilitates signal analysis such as power spectrum analysis and filter simulation by means of digital computers. If a given time signal is broken up into data segments Δt seconds long, then the square of the discrete fourier transform of a segment divided by the time increment Δt gives the approximate power spectrum of that data segment. By averaging m data segments then an integration improvement can be realized which compares to the averaging time t in the previous described detection equation. The resolution of such a transform is approximately

the reciprocal of the time increment Δt. In application then, to monitoring the SAR band, a 50 hertz resolution implies a data segment of 20 miliseconds. From the Nyquist criteria a time domain function sampled at a periodic rate can be reconstructed from the samples provided the sampling rate is at least twice the highest frequency present. This means the data in each Δt segment must be sampled at this rate. Present technology shows that a sampling rate of 100 kilo hertz is available in a FFT digital computer. Since the SAR band is 100 kilo hertz wide, a scheme for translating this band to below 50 kilo hertz must be used prior to applying the FFT computer. Figure 21 is a possible scheme for splitting the SAR band into two 50 kHz bands and translating each half down to 0 to 50 kilo hertz. From the block diagram it can be seen that a continuous display of the entire SAR band is available. Circuitry could be designed to recognize a signal detection only in the bandwidths of ambiguity of each A/R tone. Even though the block diagram shows two FFT computers, a cheaper option would be to multiplex both halves of the SAR band into one FFT computer.

D. SARCOM TRACKING

It was previously shown that the bandwidth of ambiguity for an A/R tone results from oscillator instabilities and doppler shifts. Since each OMEGA tone is translated in frequency by a signal derived from the same local oscillator that generates the A/R tone, then the OMEGA tones also shift in frequency the same rate and direction as does the A/R tone. A scheme of tracking the A/R tone will also track out the frequency shifts in the OMEGA tones. A phase-locked-loop (PLL) receiver is such a method.

Sarcom tracking is a two step process for the PLL receiver. Step one is the acquisition phase in which the PLL must acquire the A/R tone. The

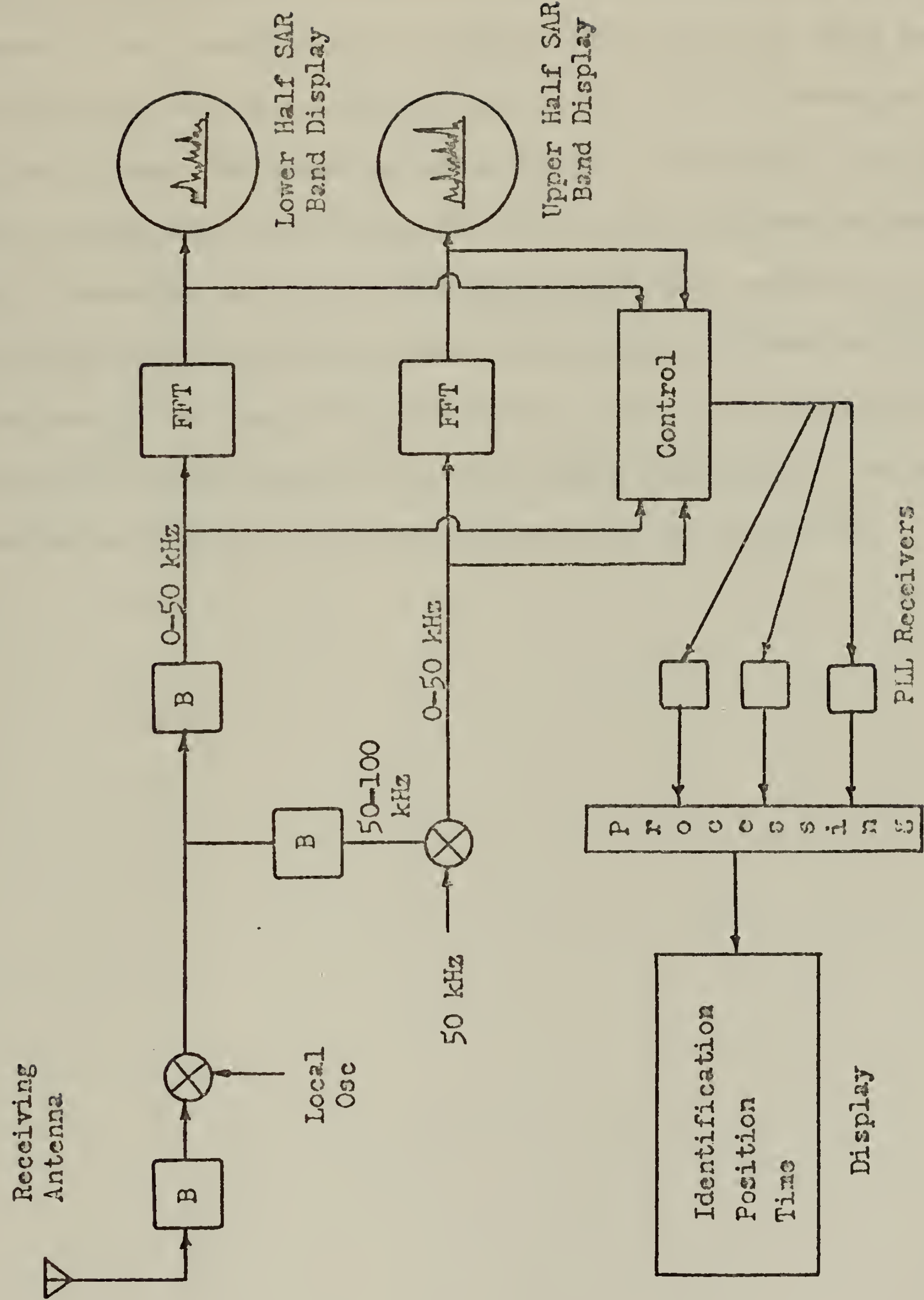

Figure 21 Fast Fourier Transform (FFT) Block Diagram Monitoring Scheme

acquisition bandwidth and SNR determine the time to acquire and lock on to the A/R tone. In the GRAN feasibility tests conducted by the Naval Air Test Center (NATC), Patuxent River, Maryland, an acquisition bandwidth of 300 Hertz was employed which gave acquisition probability greater than 98 percent with a power level of 4 watts in the A/R tone. Step two of the tracking process is maintaining lock on the A/R tone throughout the OMEGA data phase. The tracking bandwidth of a PLL receiver can be decreased considerably after acquisition and lock up has been achieved. The tracking bandwidth used in the NATC GRAN feasibility tests was 10 Hertz. Experimental results from these tests showed that the receivers held lock 99.5 percent of the time with power levels as low as 35 milliwatts in the A/R tone. The actual acquisition and tracking bandwidths to be employed in the GRAN system is an area for further tests and evaluation.

VI. LINK CONSIDERATIONS

Up to now each section of the proposed GRAN system has been looked at as a separate entity. The system must be treated as a whole to determine the optimum system parameters. From the previous chapters some conclusions have been drawn from which assumptions will be made in this chapter. The following analysis is based on these lead-in assumptions.

(1) Normal mode of operation of a SARSAT will be transponded noise 91.1 percent of the time with only one channel active 8.49 percent of the time and more than one channel active 0.41 percent of the time.

(2) The link derivation in this chapter will be based on only one active channel with the probability of interference on one channel equal to .00233 as was shown in II.E.2.

(3) The proposed SARCOM design calls for 5 watts output power. The power division will be 10 percent in the A/R tone with the remaining 90 percent divided equally between the OMEGA tone channels during the OMEGA data mode.

(4) The SARSAT translating repeater will be a hard limiting amplifier.

In deriving the overall general link equation all parameters will be represented as symbols. The simplified link equation can then be obtained by using values based on assumptions, design specifications, experimental and predicted data. The items to be examined in this chapter are link losses and gains, noise and signal reference, link equations and sample link calculations.

A. LINK LOSSES AND GAINS

Path loss, off-beam loss, feed and line loss and polarization loss will be the link losses considered. The antenna gains and power outputs will be the link gains. Then lumping all these factors together an overall link factor for the uplink and the downlink will be determined.

1. Path Loss

Path loss, "spreading loss," or more commonly free space loss is a factor defined as the ratio of the received power to the transmitted power between isotropic antennas. From this definition it can be shown that free space loss is

$$L_{fs} = \frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi R}\right)^2 \tag{16}$$

where P_r is the received power in watts, P_t is the transmitted power in watts, λ is the wavelength in same units as R, and R is the distance between the antennas. Replacing λ by v/f (velocity of propagation/frequency) and converting to dB the result is

$$L_{fs}(\mathrm{dB}) = -[37.80 + 20 \log f + 20 \log R]$$

where f is in MHz. and R is in n.mi. The actual free space loss depends only on omnidirectional spreading of energy. The frequency dependence enters from the definition of antenna effective area in the derivation of (16). The expression for free space loss is the same for uplink and downlink calculations.

2. Off-Beam Loss

Off-beam loss is loss due to misalignment of an antenna beam center with its intended target. The SARCOM off-beam loss and SARSAT off-beam loss will be functions of the satellite elevation angle. Both off-beam losses will also depend on the antenna patterns. At the SARSAT it is assumed that a wider than earth coverage beam will be used. This will make the size of the antenna required smaller as was shown in IV.A.2. but with a reduction in center beam and edge coverage gains. The overall off-beam loss on the uplink will be assumed to be negated by the SARCOM antenna gain. Hence using a 0 dB reference for SARCOM antenna gain will account for off-beam losses on the uplink.

In the downlink the positions of the SARSAT and SARCEN are known. If the downlink frequency is such that a common antenna is used on the SARSAT for receiving and transmitting then the off-beam loss will be just the off-beam loss of the SARSAT antenna. This off-beam loss will depend on how far the SARCEN is from the satellite subpoint. If the downlink frequency is high enough to require a separate antenna then the off-beam loss in the downlink can be neglected since the antennas will be assumed to be in alignment.

3. Feed and Line Losses

Feed and line losses are associated with hardware and plumbing in transferring power between the receiving antenna and input amplifier or between the output amplifier and transmitting antenna. This loss becomes significant when a long transmission line run exists and/or couplers and switches exist between the amplifier and antenna. For the SARCOM unit this loss is negated by specifying a 5 watt power output into the antenna. At the SARSAT, feed and line loss affects input signal and transponded VLF noise equally. Since the VLF noise is the dominant factor then the SARSAT feed and line loss is neglected.

In the downlink a specification of SARSAT transmit power will imply power delivered to the antenna as in the SARCOM unit. At the SARCEN the received signal and transponded noise will determine the SARCEN G/T requirements for negligible degradation as will be shown later in this chapter. Thus, the downlink feed and line losses are neglected also.

4. Polarization Loss

Polarization loss is loss due to the departure from circularity in both the transmit and receiving antennas. For transmission between circular polarized antennas (same polarization) this loss is small and

is assumed to be -0.2 dB. for the uplink. The polarization loss in the downlink will be assumed to be the same as for the uplink.

5. Link Gains

The free space loss was defined in terms of an ideal isotropic antenna for both the transmitting and receiving antennas. Defining the ratio of the effective area of a given antenna to the area of an isotropic antenna as the antenna gain the result is [25].

$$G = \frac{4\pi A_e}{\lambda^2} \tag{17}$$

In (17) A_e is the effective area of the antenna and accounts for antenna efficiency. The symbol λ is again the wavelength. From (17) it can be seen that the gain is directly proportional to A_e and as frequency is increased so does the gain since frequency is inversely proportional to wavelength. For a fixed antenna the free space loss increases at the same rate as does the antenna gain, however, for a link two antennas are involved hence the overall link gain increases with frequency provided the effective antenna areas remain constant.

6. Link Factors

If all the preceding factors are considered together a resultant link factor can be defined which will be used in the general link equation. Define uplink factor, L_u, and downlink factor, L_d, as the ratio of the received power to the transmitted power with losses considered. Then

$$L_u = G_{ts}G_{rB}L_{fsu}P_u$$

$$L_d = G_{tB}G\,L_{fsd}P_d \tag{18}$$

Where

G_{ts} = SARCOM transmit antenna gain

G_{rB} = SARSAT receive antenna gain

L_{fsu} = uplink free space loss

p_u = uplink polarization loss

G_{tB} = SARSAT transmit antenna gain

G = SARCEN receive antenna gain

L_{fsd} = downlink free space loss

p_d = downlink polarization loss

B. NOISE AND SIGNAL REFERENCE

Charts for expected atmospheric noise at 10 kilo hertz are contained in reference [26]. These charts cover four hour intervals from 0000 to 2400 GMT and span three months at a time. From these charts a noise reference of -95 dB relative to one volt per meter in a one hertz bandwidth will be used as the VLF noise reference. This converts to a noise power density of -120.8 dBw per meter squared in a one hertz bandwidth. This figure is representative of the median value obtained from these charts. Values ranged from a minimum -110 dB to a maximum of -88 dBv/m-Hz. However, the majority of the areas ranged from -100 dB to -90 dBv/m-Hz. It can be shown that the SARCOM front end noise is negligible compared to the received VLF noise.

The noise reference for both the SARSAT and SARCEN will be the system effective temperature. The resulting noise power density is given by

$$N = kT \text{ watts/Hz} \tag{19}$$

where k Boltzmann's constant (-228.6 dBw/Hz-K), T is the effective system temperature in degrees Kelvin, and B is the effective noise bandwidth in

hertz. The resultant noise power then is found by multiplying (19) by the noise bandwidth B.

The information in reference [27] is experimental data and theoretical data generated by computer simulation for OMEGA field strength as a function of distance from the transmitter. The data is tabulated as dB relative to one microvolt per meter. Averaging the data at 4000 n.mi. gives a field strength which converts to a power density of -102.6 dBs/m^2 for a 10 kilowatt radiated power. The signal reference used later in this chapter will be -120.8 dBw/m^2 which is over 18 dB worse than the average figure. This reference value also is the next to worst data point in the OMEGA data. By choosing this reference value for OMEGA signal strength the resulting SNR at the input to the SARCOM unit will be 0 dB and can be assumed to be nearly worst case.

C. OVERALL LINK EQUATIONS

The equations of interest involve two phases of the GRAN format. They are (1) the alert phase in which only the A/R tone is transmitted at the full power of the SARCOM transmitter, and (2) the OMEGA data phase in which the A/R tone receives 10 percent of the SARCOM power and the OMEGA tone channels divide the remaining 90 percent of the power equally. Figure 22 is a depiction of the total GRAN system with symbols identifying some of the different parameters. The list of symbols that is used in this figure and the following sections is enumerated in Table IX. The end results will not necessarily include all of these symbols. In particular the simplified equations will have most of the symbols replaced by their respective reference values or design values.

In determining the power transmitted from a hard-limited amplifier for which the output power is constant, the following relationship is

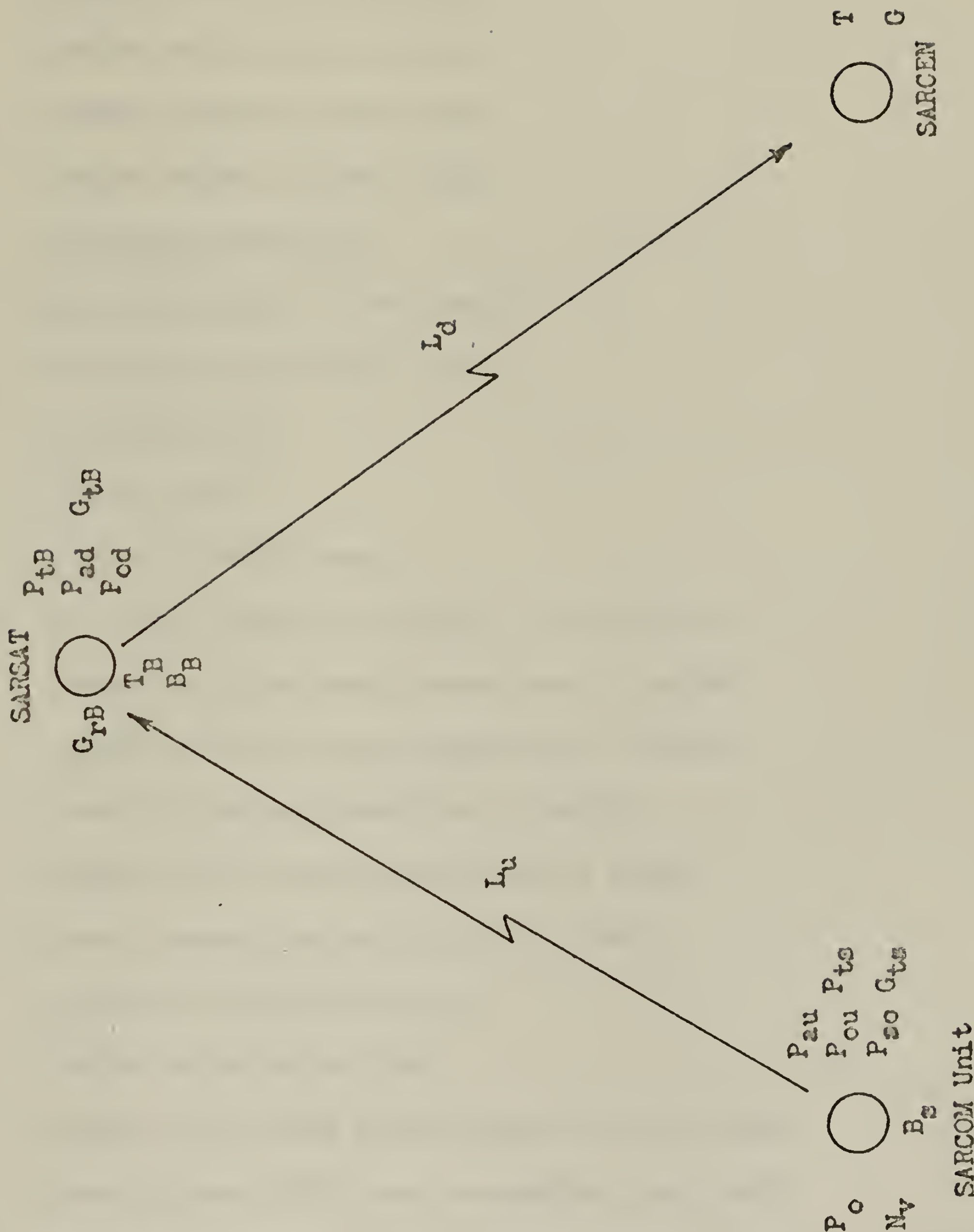

Figure 22 GRAN System with Link Symbols

Symbol	Meaning
B_B	noise bandwidth of SARSAT ("BIRD")
B_s	bandwidth of an OMEGA tone filter
f_d	downlink frequency
G	SARCEN receive antenna gain
G_{rB}	SARSAT receive antenna gain
G_{tB}	SARSAT transmit antenna gain
G_{ts}	SARCOM transmit antenna gain
k	Boltzmann's constant
L_{fsd}	free space loss in the downlink
L_{fsu}	free space loss in the uplink
L_d	downlink factor
L_u	uplink factor
n	number of OMEGA tones
N_v	VLF noise density at SARCOM in watts/m^2-Hz
N_{vu}	total VLF noise power transmitted at SARCOM
N_{vd}	total VLF noise power transmitted at SARSAT
N_{ud}	total UHF noise transmitted at SARSAT
P_{ad}	power in A/R tone transmitted from SARSAT
P_{au}	power transmitted in A/R tone at SARCOM
p_d	downlink polarization loss
p_u	uplink polarization loss
P_{od}	power in one OMEGA tone transmitted from SARSAT
P_{ou}	power in one OMEGA tone transmitted from SARCOM
P_o	power density of an OMEGA tone at input to SARCOM in watts/m^2
P_{so}	total power in n OMEGA channels each of bandwidth Bs at the SARCOM unit

Table IX. Symbols and Definitions

Symbol	Meaning
P_{tB}	total power transmitted from SARSAT
P_{ts}	total power transmitted from SARCOM
R_A	SNR in a one hertz bandwidth for the A/R tone during the alarm phase
R_{AD}	SNR in a one hertz bandwidth for the A/R tone during the OMEGA data phase
R_O	SNR in a one hertz bandwidth for one OMEGA tone
T_B	SARSAT effective front end noise temperature
T	SARCEN effective front end noise temperature

Table IX. Symbols and Definitions (continued)

derived. Define the power output in some signal of interest as S_o watts. The remaining output power is other signal information and noise defined as N_o watts. In other words everything else is considered noise with respect to the signal of interest. Then total output power P is equal to the sum of N_o and S_o.

$$P = S_o + N_o$$

Solving for S_o

$$S_o = \frac{P}{1 + \frac{N_o}{S_o}} \tag{20}$$

In (20) N_o/S_o is the inverse of SNR at the output of the amplifier. It has been shown in references [21-23] that SNR_o can be replaced by SNR_1, the SNR at the input, times a factor α.

$$S_o = \frac{P}{1 + \frac{1}{\alpha \frac{S_i}{N_i}}} \tag{21}$$

For a hard-limiting amplifier this constant α varies from -1.05 dB for input SNR much less than unity to 3.01 dB for input SNR much greater than unity. This SNR refers to total power in the signal bandwidth and total power in the noise bandwidth and not SNR in a one hertz bandwidth. It will be seen later that the input SNR into the SARCOM and SARSAT are less than unity by a considerable amount over the noise bandwidths. By setting α equal to -1.05 dB in (21) the result is

$$S_o = \frac{P}{1 + \frac{1}{0.785 \frac{S_i}{N_i}}} = \frac{P}{1 + 1.274 \frac{N_i}{S_i}} \tag{22}$$

The only exception to this is the alarm phase in which SNR is such that degradation is not greater than -0.2 dB, thus α is replaced by -0.2 dB in (21) to get

$$S_o = \frac{P}{1 + \dfrac{1}{0.955 \dfrac{S_i}{N_i}}} = \frac{P}{1 + 1.047 \dfrac{N_i}{S_i}} \tag{23}$$

1. <u>Alarm Link</u>

The alarm link is the first phase of the GRAN format in which detection must take place. The total power of the SARCOM unit is transmitted in the A/R tone. Hence at the input to the SARSAT the A/R tone is decreased only by the uplink factor, L_u. The front end noise power at the SARSAT is kT_BB_B. The portion of the power in the A/R tone transmitted in the downlink is found by using (23).

$$P_{ad} = \frac{P_{tB}}{1 + 1.047 \dfrac{kT_BB_B}{P_{au}L_u}} \tag{24}$$

The power in the UHF noise in the downlink is obtained as $P_{tB} - P_{ad}$ which is

$$N_{ud} = P_{tB} - \frac{P_{tB}}{1 + 1.047 \dfrac{kT_BB_B}{P_{au}L_u}} = P_{tB} \left[1 + \frac{0.955\, P_{au}L_u}{kT_BB_B} \right]^{-1} \tag{25}$$

At the SARCEN station the SNR for the A/R tone in a one hertz bandwidth is found by taking the ratio of the received A/R tone power to the sum of the transponded UHF noise density and the SARCEN front end noise density. Define this SNR as R_A, the SNR for the A/R tone in the alert phase.

$$R_A = \frac{P_{ad}L_d}{\dfrac{N_{ud}L_d}{B_B} + kT} \tag{26}$$

By substituting (24) and (25) into (26) and using (18), (26) can be manipulated into a function of G/T. The result is

$$R_A = \frac{F}{1 + \dfrac{H}{(G/T)P_{tB}G_{tB}L_{fsd}}} \tag{27}$$

where the constants F and H are

$$F = \frac{P_{au}L_u}{1.047\ kT_B} \tag{28}$$

$$H = \frac{kB_B}{P_d}\left(1 + \frac{0.955\ P_{au}L_u}{kT_BB_B}\right) \tag{29}$$

2. <u>OMEGA Data Link</u>

The OMEGA data link is phase three of the GRAN format where the A/R tone is transmitted at 10 percent of the SARCOM power and the OMEGA tone channels divide the other 90 percent of the power equally. In this phase the two equations of interest are (1) SNR for the A/R tone defined as R_{AD} and (2) SNR for one OMEGA tone defined as R_O, where both SNRs are in a one hertz bandwidth.

The inputs to the SARCOM unit in this phase are the n OMEGA tones and the VLF noise power. Using (22) the power output in one OMEGA tone from the SARCOM unit is

$$P_{ou} = \frac{P_{so}/n}{1 + 1.274\left(\dfrac{N_vB_s}{P_o}\right)} \tag{30}$$

The power output in the VLF noise transmitted in the uplink is found as in obtaining (25). The result is after simplification

$$N_{vu} = P_{so}\left(1 + \frac{.785\ P_o}{N_vB_s}\right)^{-1} \tag{31}$$

The power output in the A/R tone is the assigned 10 percent of the total power and is given by the symbol P_{au}.

At the input to the SARSAT the sources of power are the n OMEGA tones, the transponded VLF noise, the A/R tone, all degraded by the uplink factor and the SARSAT front end noise power. Applying (22) to the A/R tone and one OMEGA tone the resulting power output from the SARSAT follows.

$$P_{ad} = \frac{P_{tB}}{1 + 1.274\left(\frac{N_{vu}L_u + nP_{ou}L_u + kT_BB_B}{P_{au}L_u}\right)} \tag{32}$$

$$P_{od} = \frac{P_{tB}}{1 + 1.274\left(\frac{(n-1)P_{ou}L_u + N_{vu}L_u + P_{au}L_u + kT_BB_B}{P_{ou}L_u}\right)} \tag{33}$$

In determining the power transmitted in the downlink VLF noise and UHF noise it can be shown that for the reference values chosen for the probable system parameters and the VLF noise reference that these two powers are comparable. The result then is that no degradation occurs in going through the SARSAT transponder hence the constant in (21) is replaced by unity. Therefore using (21) the VLF and UHF power outputs from the SARSAT are as follows.

$$N_{vd} = \frac{P_{tB}}{1 + \left(\frac{nP_{ou}L_u + P_{au}L_u + kT_BB_B}{N_{vu}L_u}\right)} \tag{34}$$

$$N_{ud} = \frac{P_{tB}}{1 + \left(\frac{nP_{ou}L_u + P_{au}L_u + N_{vu}L_u}{kT_BB_B}\right)} \tag{35}$$

At the SARCEN station then these powers transmitted from the SARSAT are received with the degradation of the downlink factor, L_d. The

OMEGA tone SNR, R_O, in a one hertz bandwidth is the ratio of the received power in one OMEGA tone to the sum of the received VLF and UHF noise densities plus the SARCEN front end noise density, kT.

$$R_O = \frac{P_{od} L_d}{\dfrac{N_{vd} L_d}{nB_s} + \dfrac{N_{ud} L_d}{B_B} + kT} \tag{36}$$

Now by substituting (33), (30), (31), (34) and (35) into (36) and using (18) as before, then after considerable manipulation the result is

$$R_O = \frac{F'}{1 + \dfrac{H'}{(G/T) P_{tB} G_{tB} L_{fsd}}} \tag{37}$$

where

$$F' = \frac{x}{yz}$$

and

$$x = nB_s \left(1 + \frac{0.785\ P_o}{N_v B_s}\right) \left(1 + \frac{P_{au}}{P_{so}} + \frac{kT_B B_B}{P_{so} L_u}\right) \left(B_B\right) \left(1 + \frac{P_{ts} L_u}{kT_B B_B}\right)$$

$$y = \left[1.274n \left(1 + \frac{1.274 N_v B_s}{P_o}\right) \left(1 + \frac{P_{au}}{P_{so}} + \frac{kT_B B_B}{P_{so} L_u}\right) - .274\right]$$

$$z = \left[nB_s \left(1 + \frac{0.785\ P_o}{N_v B_s}\right) \left(1 + \frac{P_{au}}{P_{so}} + \frac{kT_B B_B}{P_{so} L_u}\right) + B_B \left(1 + \frac{P_{ts} L_u}{kT_B B_B}\right)\right]$$

and

$$H' = \frac{knB_s \left(1 + \dfrac{0.785\ P_o}{N_v B_s}\right) \left(1 + \dfrac{P_{au}}{P_{so}} + \dfrac{kT_B B_B}{P_{so} L_u}\right) \left(B_B\right) \left(1 + \dfrac{P_{ts} L_u}{kT_B B_B}\right)}{P_d \left[nB_s \left(1 + \dfrac{0.785\ P_o}{N_v B_s}\right) \left(1 + \dfrac{P_{au}}{P_{so}} + \dfrac{kT_B B_B}{P_{so} L_u}\right) + B_B \left(1 + \dfrac{P_{ts} L_u}{kT_B B_B}\right)\right]}$$

The A/R tone SNR, R_{AD}, in a one hertz bandwidth during this OMEGA data phase is the ratio of the received A/R tone power to the sum of the received UHF noise density and the SARCEN front end noise density, kT.

$$R_{AD} = \frac{P_{ad}L_d}{\frac{N_{ud}L_d}{B_B} + kT} \tag{38}$$

In (38) the substitutions of (32), (30), (31) and (35) are made and using (18) again the now familiar form appears for R_{AD}.

$$R_{AD} = \frac{F''}{1 + \frac{H''}{(G/T)\ P_{tB}G_{tB}L_{fsd}}} \tag{39}$$

Where the constants F" and H" are

$$F'' = B_B \left(1 + \frac{P_{ts}L_u}{kT_B B_B}\right)\left(\frac{1}{1 + 1.274 \quad \frac{P_{so}}{P_{au}} + \frac{kT_B B_B}{P_{au}L_u}}\right)$$

$$H'' = \frac{kB_B}{P_d}\left(1 + \frac{P_{ts}L_u}{kT_B B_B}\right)$$

D. SARCEN G/T

From the previous section (27), (37), and (39) can be plotted to characterize the GRAN link. These three equations all have the same form and will plot as the same shape curve for any set of parameters. A set of reference values are chosen that are representative of the nominal system parameters. These nominal parameters are listed in Table X. From these parameter values the G/T curves are plotted in Figure 23. Now by determining how each of the curves shift as a parameter is varied a set of rules can be complied to determine G/T for the specific parameters. Alternatively G/T can be specified and a set of parameters can be found or any combination of trade-offs can be constructed. If it is desired to vary the nominal reference values also then different constant values will result in (27), (37), and (39) but the curves will still have the same shape.

In the following some of the nominal values in Table X are justified.

(1) The allocated SARSAT bandwidth B_B is 100 kHz, however, realistically the noise bandwidth will be 200 kHz.

(2) The SARSAT front end noise temperature T_B of $500^{\circ}K$ is realistic for a transistor front ent at UHF.

(3) The free space loss in the downlink is based on a SARCEN station located at the satellite subpoint. To off-set this the uplink factor is computed for edge of coverage of the SARSAT.

(4) The SARSAT receive antenna gain is taken for a 9 foot diameter parabola.

(5) For a nominal configuration assume a common antenna at the SARSAT for transmitting and receiving. Also assume that the downlink frequency is 356 MHz. The uplink frequency of 406 MHz has already determined the antenna size to obtain earth coverage for reception. Therefore for this size of 9 feet the downlink gain at 356 MHz will be 17.5 dB. If a separate antenna were to be used, as would be necessary at higher frequencies, the downlink frequency and antenna gain can be specified independently.

(6) The VLF noise and OMEGA signal references were discussed in section B of this chapter. This value of the OMEGA signal is over 18 dB worse than the average value as given previously. This means the curves generated here will be for almost worst case condition. The particular value was chosen to give a 0 dB SNR in a one hertz bandwidth at the input to the SARCOM.

(7) The SARCOM transmit gain of 0 dB was discussed in A.2. of this chapter.

Symbol	Reference Value	
B_B	53.0 dBHz	200 kHz
B_s	20 dBHz	100 Hz
f_d	65.5 dBHz	356 MHz
G_{rB}	19.2 dB	
G_{ts}	0 dB	
G_{tB}	17.5 dB	
k	-228.6 dBw/Hz-K	1.380×10^{-23} watts/Hz-K
L_{fsd}	-174.6 dB	3.507×10^{-18}
L_u	-158 dB	1.585×10^{-16}
N_v	-120.8 dBw/Hz-m^2	8.395×10^{-13} watts/Hz-m^2
n		3 or 4
P_{au}	7.00 dBw/-3.0 dBw	5 watts (alarm phase)/ 0.5 watts OMEGA Data Phase)
p_d	-0.2 dB	.955
P_o	-120.8 dBw/m^2	8.395×10^{-13} watts/m^2
P_{so}	6.5 dBw	4.5 watts
P_{tB}	10 dBw	10 watts
P_{ts}	7.00 dBw	5 watts
T_B	27.0 dB K	500° Kelvin

Table X. Reference Values for G/T Curves

Figure 23 is the graph of the G/T curves of (27), (37), and (39). From the reference values in Table X the constants were evaluated and are tabulated in Table XI.

Constant	Reference Value for Figure 23	
F	1.0976×10^{5}	50.4 dB
H	4.4776×10^{-18}	-173.5 dB
F'	0.6144 0.6138	-2.1 dB (n = 3) -2.1 dB (n = 4)
H'	1.3276×10^{-20} 1.7684×10^{-20}	-198.8 dB (n = 3) -195.5 dB (n = 4)
F"	9.0841×10^{3}	39.6 dB
H"	4.5498×10^{-18}	-173.4 dB

Table XI. Constants for SNR Equations

Refer to (16) in section A.1. of this chapter. From (16) it is clear that L_{fsd} is inversely proportional to the square of the downlink frequency. By examining the form of the SNR equations, (27), (37), and (39), it is clear that the "breakpoint" of the curves in Figure 23 will slide left or right with respect to G/T as the parameters P_{tB}, G_{tB}, and L_{fsd} are varied. The following rules are compiled for sliding the curves in Figure 23.

(1) The curves shift to the left by the same amount in dB as the increase in G_{tB} in dB. (Note: By holding frequency fixed this implies varying the size of the transmit antenna on the SARSAT).

(2) The curves shift to the left by the same amount in dB as the increase in P_{tB} in dB.

(3) The curves shift to the right in dB by twice the increase in downlink frequency in dB. (Note: This assumes separate antennas for receiving and transmitting at the SARSAT so that the transmit antenna gain can be specified independently as mentioned previously. If the downlink antenna is the same as the uplink antenna on the SARSAT then a new gain for

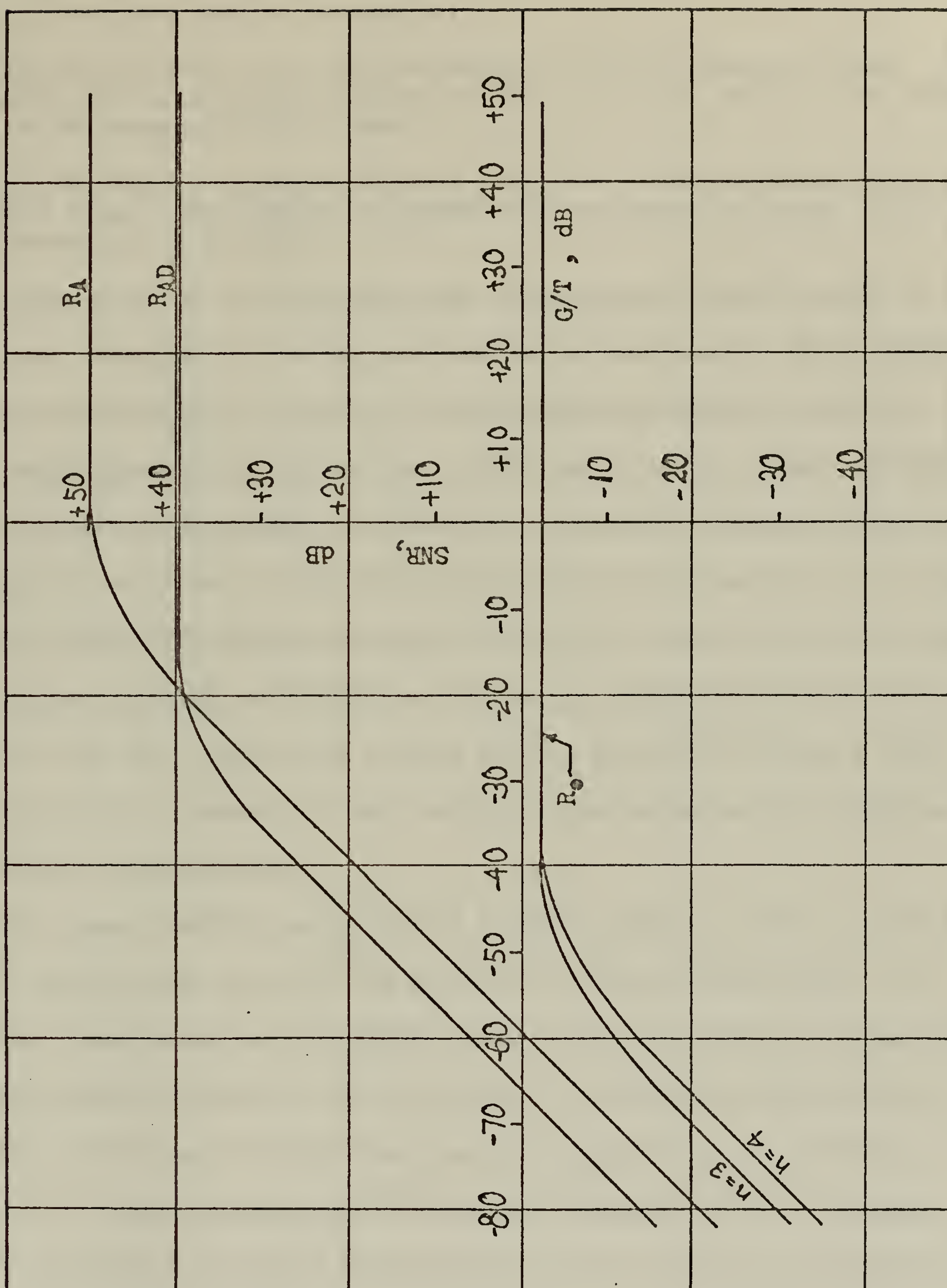

Figure 23 G/T Curves for a SARCEN

G_{tB} will have to be determined based on that antenna size and the appropriate shift to the left used as in rule 1.)

(4) The A/R tone curves are unchanged for 3 or 4 frequency OMEGA. This is due to the assignment of 10 percent of the power to the A/R tone regardless of the number of OMEGA tones.

(5) The OMEGA tone curves for $n = 3$ and $n = 4$ reach a common limit as G/T gets large. The difference between the two curves for small G/T is approximately 3 dB in SNR.

From Table X it can be determined that the reference OMEGA tone SNR in a one hertz bandwidth is 0 dB as has been stated previously. If the SARCEN G/T is increased until there is no further improvement in R_o then the only degradation to R_o will be the degradation in going through the SARCOM hard-limiter and the SARSAT hard-limiter. It would be expected that this degradation would be -2.10 dB [21-23] and Figure 23 shows this is the case.

The SARCOM unit design and specifications are fairly firm at this time. The uplink frequency of 406 MHz is fixed as is the SARSAT allocated bandwidth of 100 kHz. The uplink antenna size is also fixed within a small range since it is desired to have earth coverage antennas for receiving the SARCOM transmissions.

That means that the parameters of interest that are left to be determined are the ones for which the previous rules were established. By varying these parameters the SARSAT power output, the SARSAT antenna gain, and the downlink frequency can be picked. The simplified SNR equations are (27), (37), and (39) with the constants replaced by the values in Table XI. These constants are the values determined from the reference values in Table X for which the reference curves in Figure 23 were plotted. These curves pertain to nearly a worst case situation for OMEGA SNR at the SARCOM unit. To modify the curves for other parameters requires only recalculating the constants in Table XI. The same rules would then apply to the new reference curves for varying the parameters of SARSAT

antenna gain G_{tB}, SARSAT power output P_{tB}, and downlink frequency. It is noted from the curves that improvement in SNR results as G/T is increased up to a point. The OMEGA tone SNR curves reach their limits before the A/R tone curves do. This means for the specified power output in the A/R tone as presented in this chapter, that increasing G/T at the SARCEN to obtain the most improvement in the A/R tone SNR insures that the most improvement in the OMEGA tone SNR is also obtained. An important result to note is that degradation to the OMEGA tone SNR is the degradation due to the hard-limiters in the SARCOM and SARSAT for less than unity SNR in the noise bandwidth. This degradation is at most -2.10 dB and hence the accuracy of the GRAN system is only slightly degraded from that of the OMEGA system.

This degradation is not necessarily bad, however, because noise spikes are greatly suppressed in going through the hard-limiters.

VII. SUMMARY

The stated objectives of the GRAN system to provide continuous global coverage for the isolated distress case can be accomplished. In chapter two it was shown that a first phase system of three equatorial geosynchronous SARSATs would leave only two spherical triangular areas at the poles not covered. This phase one system could be monitored by only two SARCEN stations provided extension to global coverage is not done. To extend the system to global coverage requires a second plane of three satellites in an inclined orbit of 56 degrees minimum. This would insure at least a 7.5° elevation angle to all SARSATs from the worst case locations. To monitor this extended system would require a minimum of three SARCEN stations. As has been pointed out, the actual number and locations of the SARCEN stations would be a political problem. Implementation of the system should center around insuring the SARCEN stations are so positioned as to monitor the complete six satellite system.

The analysis of the projected SAR statistics to 1980 showed that interference and hence multiple access will not be a problem. The probability of interference on one channel was less than 0.3 percent and the probability of more than one channel active at a time was approximately 0.41 percent. A direct result of this analysis leads to the conclusion that the SARSAT should employ a hard limiting amplifier for simplicity, cost and reliability.

Due to the frequency assignment of 406 MHz. in the uplink, the uplink antennas should be circularly polarized.

In designing the SARSAT and SARCEN, four reference curves from chapter VI can be used. These reference curves have the same basic form,

the only difference being the constants. A table of the values used is in chapter VI and is based on already specified design values, experimental and actual data, and assumptions and conclusions made in this thesis. A set of rules were given for shifting the curves in relation to changing the parameters, SARSAT power output P_{tB}, SARSAT transmit antenna gain G_{tB}, and downlink frequency. The general equations in chapter VI for these curves are simplified by substitution of values for the constants. To modify the curves for other parameters only involves recalculation of the appropriate constants as given in chapter VI.

Since the arrival of a SARCOM transmission is a random event in time and spans the SAR band of 100 kilo Hertz, the analysis in chapter V shows that a Fast Fourier Transform scheme for SAR band monitoring and detection would be very good. A single spectrum analyzer monitor is inadequate since the scan time would be excessive. The scheme of 40 separate channel filters is really the same as forty separate spectrum analyzers since the bandwidth of ambiguity in the location of a SARCOM A/R tone is much greater than the desired detection resolution.

The signal processing would be done by computer as would the timing and operation of the monitoring and detection process. A bank of phase locked loop (PLL) receivers should be employed for tracking the SARCOM transmissions. A system of tape recorders for record keeping, delayed processing, and reprocessing of signals would be very useful.

APPENDIX A

PHASE ESTIMATE IN WHITE GAUSSIAN NOISE

Let the received waveform of a sinusoid of known frequency be

$$y(t) = A \sin(\omega t + \theta) + n(t) \quad \text{for} \quad t \in [0,T] \tag{A-1}$$

where A is the amplitude of the known frequency ω with phase angle θ. The noise n(t) is white Gaussian noise with one-sided power spectral density N_o. The maximum likelihood phase estimate, $\hat{\theta}$, of the received OMEGA signal $A \sin(\omega t + \theta)$ is given by the following equation [8].

$$\hat{\theta} = \tan^{-1} \frac{\int_0^T y(t) \cos \omega t dt}{\int_0^T y(t) \sin \omega t dt} \tag{A-2}$$

The quadrature components are examined under the assumption of known signal as follows. Define N as the numerator of the argument in (A-2). Substituting (A-1) into (A-2),

$$N = \int_0^T A \sin \omega t \cos \theta \cos \omega t dt + \int_0^T A \cos^2 \omega t \sin \theta \, dt + \int_0^T n(t) \cos \omega t dt \tag{A-3}$$

The integration period is approximately one second each time and the lowest frequency is 10.2 kilo hertz so there are approximately 10^4 cycles in the interval [0,T]. The assumption can be made that there are an integral number of cycles in the integration period. This then allows (A-3) to reduce to

$$N = \frac{AT}{2} \sin \theta + \int_0^T n(t) \cos \omega t dt \tag{A-4}$$

Similarly for the other quadrature component, define the denominator of the argument of (A-2) as D.

$$D = \frac{AT}{2} \cos \theta + \int_0^T n(t) \sin \omega t dt$$

Then the phase estimate, $\hat{\theta}$, is

$$\hat{\theta} = \tan^{-1}\left[\frac{\frac{AT}{2}\sin\theta + \int_0^T n(t)\cos\omega t dt}{\frac{AT}{2}\cos\theta + \int_0^T n(t)\sin\omega t dt}\right] \tag{A-5}$$

Define the quadrature components of the noise as follows.

$$N_c = \frac{2}{AT}\int_0^T n(t)\cos\omega t dt$$

$$N_s = \frac{2}{AT}\int_0^T n(t)\sin\omega t dt$$

Substituting for N_c and N_s into (A-5)

$$\hat{\theta} = \tan^{-1}\left[\tan\theta\left(1 + \frac{N_c}{\sin\theta} - \frac{N_s}{\cos\theta} + \ldots \begin{matrix}\text{higher order terms}\\ \text{in } N_c,\ N_s\end{matrix}\right)\right] \tag{A-6}$$

For a fixed value of θ, $\hat{\theta}$ is a function of the random variables N_c and N_s. Since $n(t)$ is a white Guassian random process with one-sided power spectral density function $S_N(f) = N_o$ then N_c and N_s are independent Gaussian random variables with variance $E[N_c^2]$ and $E[N_s^2]$ respectively [10]. These will be calculated shortly. Under the assumption that the expected values of N_c^2 and N_s^2 are much smaller than one the higher order terms in (A-6) can be neglected, then (A-6) reduces to (A-7).

$$\hat{\theta} = \tan^{-1}\left[\tan\theta + \tan\theta\left(\frac{N_c}{\sin\theta} - \frac{N_s}{\cos\theta}\right)\right] \tag{A-7}$$

The term $\tan\theta\left[\frac{N_c}{\sin\theta} - \frac{N_s}{\cos\theta}\right]$ is small with respect to $\tan\theta$. Expanding (A-7) in a Taylor's series through the first derivative about the small term $\tan\theta\left[\frac{N_c}{\sin\theta} - \frac{N_s}{\cos\theta}\right]$ gives

$$\hat{\theta} = \theta + N_c\cos\theta - N_s\sin\theta \tag{A-8}$$

Define phase error as $\phi = \hat{\theta} - \theta$ to get

$$\phi = N_c\cos\theta - N_s\sin\theta$$

The mean squared phase error is $E[\phi^2]$.

$$E[\phi^2] = \cos^2\theta \; E[N_c^{\,2}] + \sin^2\theta \; E[N_s^{\,2}] \tag{A-9}$$

Recall the definitions of N_c and N_s then

$$E[N_c^{\,2}] = E\left[\left(\frac{2}{AT}\int_0^T n(t)\cos wt\,dt\right)^2\right]$$

$$E[N_c^{\,2}] = \frac{4}{A^2T^2}\, E\left[\int_0^T \int_0^T n(t_1)\,n(t_2)\cos wt_1 \cos wt_2\, dt_1\, dt_2\right]$$

$$E[N_c^{\,2}] = \frac{4}{A^2T^2} \int_0^T \int_0^T E(n(t_1)n(t_2)) \cos wt_1 \cos wt_2\, dt_1\, dt_2$$

$$E[N_c^{\,2}] = \frac{4}{A^2T^2} \int_0^T \int_0^T R_n(t_1-t_2) \cos wt_1 \cos wt_2\, dt_1\, dt_2$$

$$E[N_c^{\,2}] = \frac{4}{A^2T^2} \int_0^T \int_0^T \frac{N_o}{2}\, \delta(t_1-t_2) \cos wt_1 \cos wt_2\, dt_1\, dt_2$$

Carrying out the integration the result is

$$E[N_c^{\,2}] = \frac{N_o}{A^2T} \tag{A-10}$$

Similarly for N_s

$$E[N_s^{\,2}] = \frac{N_o}{A^2T} \tag{A-11}$$

Substituting for $E[N_c^{\,2}]$ and $E[N_s^{\,2}]$ into (A-9) the mean squared phase error is

$$E[\phi^2] = \frac{N_o}{A^2T} \quad .$$

The result then is that the mean squared phase error is independent of the phase of the OMEGA signal but depends on the noise density, OMEGA amplitude and observation time T. This can be related to a signal to noise ratio (SNR) by the following. The OMEGA signal is

$$S(t) = A\sin(wt+\theta)$$

Then the power in the OMEGA signal in the integration time T is

$$P = \frac{1}{T}\int_0^T S(t)^2 dt$$

$$P = A^2/2$$

So the mean squared error is

$$E[\phi^2] = \frac{N_o}{2PT}$$

Where N_o is the one-sided noise density in watts/hertz measured at the same reference point as the signal power P, and 1/T is effectively the bandwidth of the estimator.

APPENDIX B

SIGNAL TO NOISE RATIO FOR DETECTION

Consider a radiometer with bandpass of B hertz and averaging time t seconds. It can be shown that the root-mean-square deviation (standard deviation) after postdetection and integration for t seconds is $1/\sqrt{Bt}$ times the average d-c output [28]. The output standard deviation due to noise then is

$$\sigma_N = \frac{1}{\sqrt{Bt}} \times A_N \tag{B-1}$$

where A_N is the average output due to noise. The average output from the radiometer due to noise will be the predetection gain, G, times the noise average input N_{in}.

$$A_N = G\, N_{in} \tag{B-2}$$

If only the signal input is considered, the deviation in the radiometer output due to a signal input S_{in} is

$$\Delta_s = G\, S_{in} \tag{B-3}$$

Define the radiometer output deviation due to signal as some factor k times the output deviation due to noise where k is the factor that the signal must be above the noise for detection.

$$\Delta_s = k\, \sigma_N \tag{B-4}$$

By substituting (B-2) into (B-1) and (B-4) into (B-3) the result is

$$\sigma_N = \frac{1}{\sqrt{Bt}} \times G\, N_{in} \tag{B-5}$$

$$k\, \sigma_N = G\, S_{in} \tag{B-6}$$

Now substituting (B-6) into (B-5) the following S/N equation results

$$(S/N)_{in} = \frac{k}{\sqrt{Bt}} \tag{B-7}$$

The constant k is taken to be 10 for determining SNR for detection [24].

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GLOBAL RESCUE ALARM NET (GRAN)

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The Global Rescue Alarm Net (GRAN) is a proposed Search and Rescue (SAR) system. The purpose of the system is to provide real-time world-wide distress alarm, identification, and position information for the isolated distress case. In the GRAN system a link consists of a handheld Search and Rescue Communicator (SARSOM) unit, a geosynchronous Search and Rescue Satellite (SARSAT) relay, and a processing station, the Search and Rescue Central (SARCEN). This thesis is a system analysis of the proposed GRAN system to generate the broad system

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requirements. To provide global coverage the numbers and locations of SARSATs and SARCENs are determined. Based on SAR statistical data, SARCOM distribution, multiple access, and probability of interfering transmissions are examined. The SARSAT characteristics such as configuration, antenna gains, and power output are considered in relation to the overall system. From experimental and theoretical data, reference values are chosen which are representative of near-worst case from which the total link can be characterized. From this characterization, system parameters such as SARCEN G/T and SARSAT transmit power can be determined.

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